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Feldspathic lunar meteorites and their implications for compositional remote sensing of the lunar surface and the composition of the lunar crust

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Abstract—We present new compositional data for six feldspathic lunar meteorites, two from cold deserts (Yamato 791197 and 82192) and four from hot deserts (Dhofar 025, Northwest Africa 482, and Dar al Gani 262 and 400). The concentrations of FeO (or Al_2O_3) and Th (or any other incompatible element) together provide first-order compositional information about lunar polymict samples (breccias and regoliths) and regions of the lunar surface observed from orbit. Concentrations of both elements on the lunar surface have been determined from data acquired by orbiting spacecraft, although the derived concentrations have large uncertainties and some systematic errors compared to sample data. Within the uncertainties and errors in the concentrations derived from orbital data, the distribution of FeO and Th concentrations among lunar meteorites, which represent ~18 source regions on the lunar surface, is consistent with that of 18 random samples from the surface. Approximately 11 of the lunar meteorites are low-FeO and low-Th breccias, consistent with large regions of the lunar surface, particularly the northern farside highlands. Almost all regoliths from Apollo sites, on the other hand, have larger concentrations of both elements because they contain Fe-rich volcanic lithologies from the nearside maria and Th-rich lithologies from the high-Th anomaly in the northwestern nearside. The feldspathic lunar meteorites thus offer our best estimate of the composition of the surface of the feldspathic highlands, and we provide such an estimate based on the eight most well-characterized feldspathic lunar meteorites. The variable but high (on average) Mg/Fe ratio of the feldspathic lunar meteorites compared to ferroan anorthosites confirms a hypothesis that much of the plagioclase at the surface of the feldspathic highlands is associated with high-Mg/Fe feldspathic rocks such as magnesian granulitic breccia, not ferroan anorthosite. Geochemically, the high-Mg/Fe breccias appear to be unrelated to the mafic magnesian-suite rocks of the Apollo collection. Models for the formation of the upper lunar crust as a simple flotation cumulate composed mainly of ferroan anorthosite do not account for the complexity of the crust as inferred from the feldspathic lunar meteorites. *Copyright © 2003 Elsevier Ltd*

1. INTRODUCTION

Lunar meteorites are rocks found on Earth that were ejected from the Moon by impacts of meteoroids. Beginning with ALHA (Allan Hills) 81005 in 1982 (Bogard, 1983; Marvin, 1983), ~24 lunar meteorites have been identified in the past 20 yr (Table 1). The exact number is not known with certainty because many new ones have been found each year for the past several years and pairing relationships among the newest lunar meteorites have not been established.

Cosmic-ray exposure data indicate that lunar meteorites are the products of numerous impacts on the Moon, that all lunar meteorites found thus far were ejected from the Moon in the last ~10 Ma, and that most were ejected within the last 0.1 Ma (Nishiizumi et al., 1996; Polnau and Eugster, 1998). It is not known from where on the Moon any of the lunar meteorites originated; no source craters have actually been identified. Warren (1994) reasoned that most come from small craters, a few kilometers in diameter, because there have not been enough large impacts in the past few million years to produce all of the known meteorites. The arguments of Warren (1994) are even more valid today because now there is a greater variety of compositionally and lithologically distinct rocks among the lunar meteorites and modeling studies support the small-crater hypothesis (Head, 2003). We are unaware of any arguments that lunar meteorites may preferentially derive from specific regions of the Moon. Thus, the known lunar meteorites likely represent numerous widely distributed locations about the Moon. As random-point samples they provide a type of information that cannot be obtained from the well documented samples collected from known locations on the Apollo missions. In particular, the subset of feldspathic lunar meteorites (Fig. 1) likely provides information about regions of the Moon distant from the Apollo landing sites. This point, which has been made by others, will be developed further in this paper.

Two special characteristics of lunar meteorites makes them especially valuable. Most are mixtures, and most are mixtures of near surface material. Specifically, the majority are polymict breccias derived from fine-grained regolith (the regolith breccias and perhaps the fragmental breccias of Table 1). In contrast to martian meteorites, only a small fraction of lunar meteorites are igneous or plutonic rocks. Because the Moon is covered by regolith, the brecciated lunar meteorites are likely to represent the typical mineralogy and average composition of the surface of the region of the Moon from which they originate better than any igneous or plutonic rock of which the breccia is in part derived (Warren, 1994). The combination of random source locations and representative surface compositions makes lunar meteorites useful as a form of ground truth for measurements of the lunar surface made remotely.

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Table 1. List of lunar meteorites and some of their properties.

N	Name	Lunar rock type	Mass (g)	Terrestrial origin	Year	TiO_2 (%)	Al_2O_3 (%)	FeO (%)	MgO (%)	Mg' (%)	Th (ppm)	Plot
	Feldspathic:											
1	Allan Hills (ALHA) 81005	RgBr	31	Antarctica	1982	0.27	25.8	5.5	8.2	73	0.31	A
2	Yamato 791197	RgBr	52	Antarctica	1979	0.34	26.0	6.2	6.1	64	0.34	V
3a	Yamato 82192/82193/(86032)	FrBr or RgBr	37/27/	Antarctica	82-3	0.26	26.9	5.2	5.5	65	0.17	X
3b	Yamato (82192/82193)/86032	FrBr or RgBr	648	Antarctica	1986	0.16	28.7	4.3	5.2	68	0.21	Y
4	MacAlpine Hills (MAC) 88104/88105	RgBr	61/663	Antarctica	1989	0.24	28.7	4.3	4.1	63	0.39	M
5	Queen Alexandra Range (QUE) 93069/94269	RgBr	21/3	Antarctica	93/94	0.25	28.3	4.4	4.6	65	0.52	Q
6	Dar al Gani (DaG) 262	RgBr	513	Libya	1997	0.21	27.9	4.5	5.4	68	0.39	G
7	Dar al Gani (DaG) 400	RgBr or IMBr	1425	Libya	1998	0.18	29.2	3.6	4.7	70	0.34	H
8	[Dar al Gani 996] paired with another Dar al Gani?	FrBr	12	Libya	1999	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
9	Dhofar 025 [/301/304/308 paired?]	RgBr or IMBr	751/9/10/2	Oman	00/01	0.29	27	4.9	6.7	71	0.6	D
10	[Dhofar 026] paired with other Dhofars?	GrBr	148	Oman	2000	[0.2]	[30]	[4.1]	[3.9]	[63]	[0.4]	E
11	[Dhofar 081/280; /490 paired?]	FrBr	174/251/34 4/4/34/13/	Oman	99/01	0.12	[31]	[3.1]	[2.6]	[60]	[0.2]	F
12	[Dhofar 302/303/305/306/307/ 309/310/311/730/731] pairing?	IMBr?	50/81/11/4 108/36	Oman	2001	[0.2]	[29]	[3–4]	[5]	[∼70]	n.a.	
13	[Dhofar 489] paired with another Dhofar?	FrBr	34	Oman	2001	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
14	[Dhofar 733] paired with another Dhofar?	GrBr?	98	Oman	2002	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
15	Northwest Africa (NWA) 482	IMBr	1015	Morocco or Algeria	2001	0.17	29	3.8	4.2	66	0.23	N
	Mixed:											
16	Yamato 793274/981031	RgBr	9/186	Antarctica	80/99	0.7	15/18	14/12	9/9	53/57	0.9/1.1	
17	Queen Alexandra Range (QUE) 94281	RgBr	23	Antarctica	1994	0.7	16	14	8.3	52	0.9	
18	[Calcalong Creek]	RgBr	19	Australia	∼1990	[0.8]	[21]	[9]	[8]	[60]	[4]	
19	[Yamato 983885]	RgBr	289	Antarctica	1999	[0.5]	[22]	9	[8]	[61]	[2]	
	KREEP:											
20	Sayh al Uhaymir (SaU) 169	IMB, with RB	206	Oman	202	n.a.	n.a.	n.a.	n.a.	n.a.	33	
	Mare:											
21	Elephant Moraine (EET) 87521/96008	FrBr or RgBr	31/53	Antarctica	87/96	0.8	14	18	8	43	0.9	
22	Asuka 881757	MBas	442	Antarctica	1988	2.4	10.0	23	6.3	33	0.4	
23	Yamato 793169	MBas	6	Antarctica	1979	2.2	10.8	22	5.9	33	0.7	
24	Northwest Africa (NWA) 032/ [479]	MBas	∼300/156	Morocco or Algeria	99/01	3.1	9.5	23	7.5	37	1.9	
25a	Dhofar 287	MBas (a), with RgBr (b)	154	Oman	2001	[3]	[8]	[22]	[12]	[50]	n.a.	
25b						n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	
26a	Northwest Africa (NWA) 773	Olivine gabbro (a), with RgBr (b)	633	Western Sahara	2000	[0.3]	[4]	19	[26]	[71]	1.3	
26b						0.8	[9]	[19]	[14]	57	2.1	

The list contains all lunar meteorites that have been announced in *The Meteoritical Bulletin* (e.g., Russell et al., 2002, 2003) or the *Meteorite Newsletter* of the National Institute of Polar Research of Tokyo (e.g., Kojima and Imae, 2001). Commonly used abbreviations of meteorites names (e.g., ALHA) are given in parentheses. Multiple meteorites in one listing separated by a slash (/) are known or strongly suspected to be terrestrially paired (different fragments of a single meteorite fall); other yet unrecognized pairings might exist. Meteorite names in square brackets are not well characterized (abstracts only) and concentration values in square brackets are uncertain because of variability among subsamples, the data are preliminary, or the data are based on few analyses. Rock types: MBas = mare basalt or gabbro, RBr = regolith breccia, FrBr = fragmental breccia, IMBr = impact-melt breccia, GrBr = granulitic breccia. Year = the year of find or purchase. Mg' = bulk mol.% Mg/(Mg + Fe). Plot = the plot symbol used for the feldspathic lunar meteorites in several of the figures (e.g., Fig. 1). n.a. = not analyzed or reported. Not listed here is an unnamed lunar meteorite, a feldspathic regolith breccia (27.4% Al_2O_3), described by Yanai (2000) but with no indication of its mass or place of origin. The data were compiled from this work, some unpublished data of this lab (Yamato 983885 and Northwest Africa 773) and other labs (Calcalong Creek, courtesy D. Hill), and the following sources: Arai and Warren (1999), Bischoff et al. (1987, 1998), Boynton and Hill (1983), Fagan et al. (2002, in press), Fukuoka (1990), Fukuoka et al. (1986a, 1986b), Greshake et al. (2001), Hill et al. (1991), Jolliff et al. (1991a, 1998), Kaiden and Kojima (2003), Kallemeyn and Warren (1983), Koeberl (1988), Koeberl et al. (1989, 1990, 1991a, 1991b, 1993, 1996), Korotev et al. (1983, 1996), Laul et al. (1983a), Lindstrom et al. (1986, 1991a, 1991b, 1995), Nazarov et al. (2002), Nishiizumi et al. (1996), Ostertag et al. (1986), Palme et al. (1983, 1991), Russell et al. (2002, 2003); Semenkova et al. (2000), Snyder et al. (1999), Spettel et al. (1995), Takahashi and Masuda (1987), Taylor et al. (2001a, 2001b), Thalmann et al. (1996), Verkouteren et al. (1983), Warren and Kallemeyn (1986, 1991a, 1991b, 1993, 2001), Warren et al. (2001), Yanai (1991), and Zipfel et al. (1998).

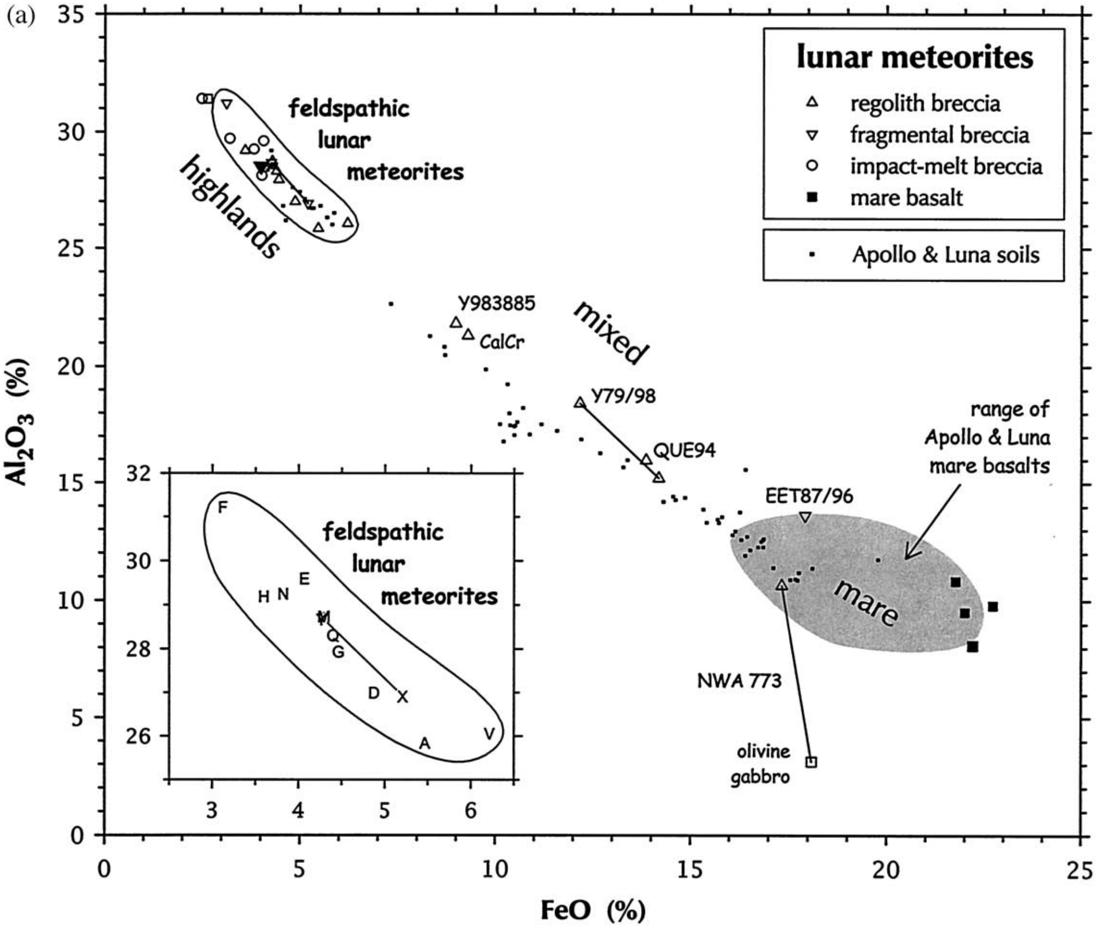

Fig. 1a. Compositional range of lunar meteorites compared to soils from the Apollo and Luna missions. Two points connected by a line are plotted for those meteorites for which different stones of a pair (Yamato 82192/82193/86032 and Yamato 793274/981031) or different lithologies within a single stone (Northwest Africa 773) differ significantly in composition. Although the soils are mixtures of three classes of lithologic components (Fig. 6), the data describe a nearly linear trend on this plot because all three lithologic components are mainly composed of the same four minerals, one high-Al, low-Fe mineral (plagioclase) and three high-Fe, low-Al minerals (olivine, pyroxene, and ilmenite). Low-FeO points correspond to meteorites from the feldspathic highlands (Fig. 1b), high-FeO points represent meteorites from the maria. Meteorites with intermediate compositions ("mixed") are breccias consisting mainly of material of both provenances. In contrast, Apollo soils of intermediate composition (particularly the cluster corresponding to Apollo 14 at 10% FeO), are not mixtures of mare and feldspathic highlands material but are dominated by Th-rich material of the Procellarum KREEP Terrane (Fig. 6a). Because of the different mineral compositions (e.g., Ca content of pyroxene, Mg/Fe ratios of olivine and pyroxene) and ratios (ilmenite/pyroxene) between mare basalts and Th-rich impact-melt breccias, there is a kink in the soil trend at 10% FeO. The key to the inset is in Table 1. The soil data are mainly from the sources of Table 1 of Korotev (1998).

In this paper we present new compositional data for six feldspathic lunar meteorites. Compositional data for three of them, Yamato 791197, Yamato 82192, and DaG (Dar al Gani) 262, have been presented by others (Fukuoka et al., 1986a; Lindstrom et al., 1986, 1987, 1991a; Ostertag et al., 1986; Warren and Kallemeyn, 1986, 1987; Bischoff et al., 1987, 1998; Koeberl, 1988). Some data on bulk composition for the other three, DaG 400, Dhofar 025, and NWA (Northwest Africa) 482, have been presented in abstracts (Zipfel et al., 1998; Bukovanska et al., 1999; Taylor et al., 2001a; Warren and Kallemeyn, 2001). We also review compositional aspects of lunar meteorites and note implications that they have for compositional remote sensing of the lunar surface and the composition of the lunar crust.

2. SAMPLES AND ANALYSIS

2.1. Feldspathic Lunar Meteorites

We obtained a small slab purported to be of DaG 262 and four small slabs purported to be of NWA 482 from meteorite dealers. We obtained a small slab identified as Dhofar 025 and a powder identified as sawdust of DaG 400 from collectors seeking authentication of their purchases. The National Institute of Polar Research (Japan) supplied chips of Yamato 791197 and Yamato 82192. We made splits of unpowdered samples using a diamond wafer saw or stainless steel chisel and agate mortar. Using INAA (instrumental neutron activation analysis), we determined the concentrations of up to 31 trace, minor, and major elements in two splits of DaG 262 (13 and 34

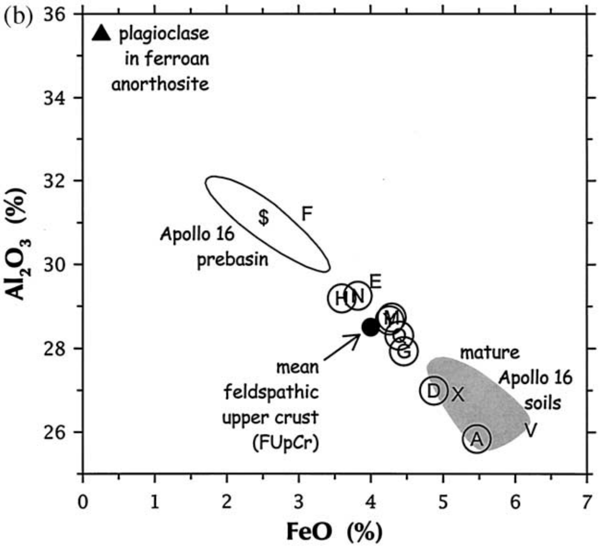

Fig. 1b. Detail of feldspathic end of the trend of Figure 1a. The letter symbols each represent a feldspathic lunar meteorite; the key is in Table 1. Those meteorites used for the FUpCr (feldspathic upper crust) estimate of Table 5 (filled circle) are circled. The FUpCr estimate lies to lower FeO than the mean of the circled points because of the meteorites contain chondritic material and the FUpCr estimate does not (section 4.4). The mean ($) and range (ellipse) of five estimates of the composition of the feldspathic, pre-Imbrium components of the Apollo 16 regolith (Stöffler et al., 1985, Table 15; Korotev, 1997, Table 10) is also shown. These estimates are substantially more feldspathic than either the present Apollo 16 soils or most of the lunar meteorites (section 4.1).

mg), two splits of the DaG 400 sawdust (25 and 68 mg), three splits of Dhofar 025 (18–28 mg), 13 splits of NWA 482 (2, 3, or 4 splits from each of the 4 slabs; mean mass = 26 mg), and three splits of Yamato 791197 (11–18 mg). Procedures for INAA were similar to those described in Korotev (1991) and Jolliff et al. (1991a). Table 2 presents mass-weighted mean concentrations obtained for these five meteorites. INAA results for the sample of Yamato 82192 and a previous allocation of Yamato 791197 were presented by Lindstrom et al. (1986, 1991a).

We have also determined concentrations of major and minor elements in splits of all six meteorites by FB-EMPA (fused-bead electron microprobe analysis) as described in Jolliff et al. (1991a), except that the samples were fused under Ar. Fused beads were analyzed at 15 kV, 30 nA, and beam spot sizes of 20 to 30 μm. Information about the identification of the fused splits is presented in Table 3 and mean results are presented in Table 4.

In the tables and throughout the paper, oxide concentrations are expressed as percent element as oxide on a mass basis. For example, the concentration of all forms of iron are expressed as FeO in units of "weight percent" (centigrams of FeO per gram of sample).

2.2. Apollo 16 Comparison Suite

Of the six Apollo missions, only Apollo 16 visited a region of feldspathic highlands distant from a source of mare basalt. Consequently, the Apollo 16 samples are compositionally most similar to the feldspathic lunar meteorites (but with some important differences that are discussed in section 4.1). As a means of comparing the feldspathic lunar meteorites to Apollo 16 samples, we present in several figures INAA data from an ongoing study of small lithic fragments from numerous regolith samples collected on the Apollo 16 mission. This study is similar to ones that we have done in the past for Apollo 14 and 17 (Jolliff et al., 1991b, 1996), and a portion of the data has been presented in Korotev (1991), Jolliff and Haskin (1995), and Korotev et al. (1997). From the set of 1011 lithic fragments, we have selected a suite of 134 that have compositions similar to the feldspathic lunar meteorites. Specifically, each fragment in the Apollo 16 suite has 3.0 to 6.5% FeO, 5 to 13 ppm Sc, 0.5 to 2.0 ppm Sm, and $<$ 350 ppm Ni. The average fragment mass is 23 mg, on the same order as the analyzed subsamples of meteorites. On the basis of their composition and on examination of some of them with a binocular microscope, we surmise that many are feldspathic breccias. About half the fragments are from sample 67513, however, and many of those fragments appear to be related petrogenetically to each other in that they likely derived from a single igneous precursor of ferroan noritic anorthosite (Jolliff and Haskin, 1995). In contrast, all of the feldspathic lunar meteorites are breccias and most are regolith breccias. As a consequence of this difference, the mean concentration of Ni in the Apollo 16 suite is only 70 ppm, which compares with ~200 ppm (range 90–315 ppm) in the feldspathic lunar meteorites because most of the Ni in polymict lunar samples derives from impact of meteoroids that lead to brecciation (section 4.3.2). With respect to lithophile elements, the feldspathic lithic fragments of the Apollo 16 comparison suite provide a set of self-consistent data (similar analyzed mass and identical analysis technique) against which to compare the meteorites.

3. RESULTS

Like the majority of lunar meteorites (Fig. 1), all six of the meteorites analyzed here are rich in aluminum (Al_2O_3 = 27–29%) and have low concentrations of incompatible elements (Tables 1 and 3). Our compositional results for DaG 262 are consistent with those of Bischoff et al. (1998) with the exceptions that both of our subsamples are severely contaminated with Au (Fig. 2). Concentrations of K, Ca, As, Br, Sr, Sb, Cs, and Ba are greater than observed in Apollo samples of otherwise similar composition (e.g., Fig. 3). As noted by Bischoff et al. (1998) and Floss and Crozaz (2001), these anomalies are the result of post-fall alteration by terrestrial weathering processes in the hot desert environment.

For DaG 400, we analyzed two subsamples (25 and 68 mg) of sawdust by INAA. On average (Table 2), our INAA values compare well with those of Zipfel et al. (1998), with the exception that our Ba concentration is 1.8 times greater, presumably from nonuniform distribution of terrestrial weathering products. DaG 400 is anomalously enriched in the same suite of elements as DaG 262. The CaO concentration that we obtained by FB-EMPA, 18.4%, is greater than the 17.0% that we obtained by INAA and is also greater than the ~16.7% that we would expect for a feldspathic lunar sample with 29% Al_2O_3. We speculate that the cause of the discrepancy is nonuniform

Table 2. Mass-weighted mean results of instrumental neutron activation analysis for 23 subsamples of 5 feldspathic lunar meteorites.

		Dar al Gani 262		Dar al Gani 400		Dhofar 025			North West Africa 482			Yamato 791197		
	Unit	Mean	±[a]	Mean	±[a]	Mean	±[a]	s.d.[b]	Mean	±[a]	s.d.[b]	Mean	±[a]	s.d.[b]
Na$_2$O	%	0.349	0.004	0.332	0.003	0.345	0.003	0.011	0.377	0.004	0.017	0.325	0.003	0.005
K$_2$O[c]	%	0.05	0.02	0.06	0.04	0.09	0.10	0.02	0.04	0.09	0.04	<0.15		
CaO	%	16.7	0.2	17.0	0.2	15.5	0.2	0.1	17.1	0.2	0.9	15.65	0.23	0.11
FeO	%	4.38	0.04	3.40	0.03	4.76	0.05	0.26	3.76	0.04	0.19	5.51	0.12	0.52
Sc	ppm	7.67	0.08	5.99	0.06	9.82	0.10	0.87	6.93	0.07	0.43	11.70	0.12	1.12
Cr	ppm	640	6	520	5	766	8	41	519	5	26	865	9	44
Co	ppm	20.10	0.2	13.84	0.14	15.39	0.15	0.50	13.21	0.13	1.18	5.51	0.06	0.52
Ni	ppm	242	5	132	7	127	9	22	144	8	24	151	11	14
As[c]	ppm	0.56	0.05	0.79	0.09	0.19	0.08	0.14	0.12	0.08	0.07	<0.2		
Br[c]	ppm	1.4	0.15	1.0	0.2	n.a.			n.a.			n.a.		
Rb	ppm	<3		<2		<5			<4			<4		
Sr[c]	ppm	202	5	268	8	2090	25	1130	171	7	9	150	12	4
Zr	ppm	27	4	28	6	52	9	11	21	6	6	30	14	1
Sb[c]	ppm	0.020	0.005	0.151	0.007	0.035	0.007	0.004	0.009	0.007	0.013	<0.03		
Cs[c]	ppm	0.049	0.007	0.043	0.009	<0.12			<0.08			<0.12		
Ba[c]	ppm	150	3	257	4	110	4	53	30	3	8	26	4	6
La	ppm	2.21	0.02	2.22	0.02	3.27	0.03	0.32	1.523	0.016	0.108	1.93	0.02	0.21
Ce	ppm	5.83	0.15	5.52	0.12	8.71	0.10	1.03	3.99	0.07	0.28	5.18	0.15	0.56
Nd	ppm	3.2	0.4	3.3	0.6	5.1	0.7	0.7	2.5	0.5	0.2	3.0	1.0	0.4
Sm	ppm	1.015	0.015	0.894	0.009	1.646	0.016	0.169	0.788	0.008	0.058	0.975	0.010	0.102
Eu	ppm	0.749	0.007	0.717	0.007	0.819	0.010	0.028	0.750	0.008	0.017	0.734	0.013	0.020
Tb	ppm	0.206	0.005	0.180	0.005	0.337	0.008	0.030	0.161	0.005	0.011	0.227	0.009	0.018
Yb	ppm	0.820	0.008	0.689	0.010	1.280	0.013	0.160	0.634	0.008	0.043	0.896	0.013	0.095
Lu	ppm	0.1212	0.0015	0.096	0.002	0.179	0.002	0.021	0.0904	0.0016	0.0067	0.127	0.003	0.017
Hf	ppm	0.738	0.010	0.628	0.013	1.26	0.02	0.26	0.582	0.013	0.116	0.73	0.02	0.05
Ta	ppm	0.099	0.005	0.12	0.02	0.134	0.010	0.017	0.066	0.007	0.007	0.099	0.016	0.009
W[c]	ppm	<1		2.0[d]	0.1	<0.7	0.2	0.0	<0.6	0.2		<0.8		
Ir	ppb	10.5	0.3	4.2	0.7	3.7	0.5	0.2	5.3	0.4	0.7	5.5	0.7	0.4
Au[c]	ppb	62	1.1	26[d]	1	7.4	0.5	2.3	3.4	0.5	2.9	1.5	0.6	0.5
Th	ppm	0.364	0.012	0.302	0.011	0.525	0.013	0.053	0.24	0.01	0.02	0.291	0.014	0.056
U	ppm	0.181	0.012	0.29	0.03	0.20	0.02	0.05	0.08	0.02	0.03	0.09	0.02	0.02
Mass[e]	mg	46.9		92.7		73.0			334.5			41.6		
N[f]		2		2		3			13			3		

[a] Estimate of the analytical uncertainty (1 standard deviation, mean) of an analysis of a single subsample based mainly on counting statistics.
[b] Sample standard deviation of all subsamples.
[c] Elements suspected of being affected by terrestrial contamination.
[d] The small subsample had 5.2 ppm W and 15 ppb Au; the large subsample had 0.8 ppm W and 30 ppb Au.
[e] Total mass of all subsamples.
[f] Number of subsamples.

distribution of terrestrial calcite, even in the sawdust. Within analytical uncertainty, the results for the two INAA subsamples are identical, except that (1) La and Ce concentrations are ~10% greater in the small subsample compared to the large subsample and (2) W and Au concentrations differ significantly (5.2 and 0.8 ppm W and 15 and 30 ppb Au in the small and large subsamples, respectively). We do not know the cause of the differences in the rare earth elements, but it may from nonuniform distribution of terrestrial weathering products (section 4.3.3). On the basis of the low concentrations observed in Apollo rocks and lunar meteorites from Antarctica of otherwise similar composition (Fig. 2), we conclude that nearly all the W and most of the Au that we observe are contaminants from sawing (tungsten carbide?) and handling (jewelry).

Our results for Dhofar 025 are largely consistent with those of Taylor et al. (2001a) and Warren et al. (2001) except that our results for Eu (0.82 ppm) do not confirm the unusually high concentration (1.3 ppm) reported by Taylor et al. (2001a).

Table 3. Identification of splits used for major element analysis of "fused beads" by electron microprobe analysis.

Meteorite	Split identification	*N*	*M*
DaG 262	All of the 13-mg INAA split	2	15
DaG 400	20-mg split of unirradiated sawdust	2	12
Dhofar 025	All of the 28-mg INAA split	2	17
Dhofar 025	4-mg split of unirradiated material	1	7
NWA 482	17-mg split of unirradiated material	2	14
Yamato 791197	8-mg INAA split (89,4) of Lindstrom et al. (1986)	1	10
Yamato 82192	11-mg INAA split (141A1) of Lindstrom et al. (1991a)	1	8
Yamato 82192	16-mg INAA split (141A2) of Lindstrom et al. (1991a)	2	15

N is the number of subsplits ("beads") fused from each split; *M* is the total number of spots analyzed by EMPA on all subsplits.

Table 4. Mean results of electron microprobe analysis of "fused beads" (FB-EMPA).

	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Σ	*Mg′*	Mass
DaG 262	43.8	0.20	28.4	0.08	4.47	0.06	5.50	17.10	0.35	0.052	0.06	100.0	69	12.9
DaG 400	43.5	0.18	28.8	0.08	3.62	0.07	4.62	18.44	0.34	0.090	0.22	100.0	70	20
Dhofar 025[a]	44.2	0.29	26.9	0.11	4.90	0.05	7.10	16.20	0.35	0.039	0.06	100.1	72	31.5
NWA 482	43.9	0.16	29.4	0.10	3.80	0.05	4.28	18.47	0.26	0.035	0.04	100.5	67	17
Yam 791197	44.9	0.40	27.3	0.11	5.71	0.12	5.76	15.86	0.30	0.028	0.02	100.5	64	8
Yam 82192[a]	45.2	0.21	28.3	0.13	4.40	0.08	5.18	16.13	0.42	0.026	0.03	100.1	68	27.5
Stnd. Dev.	0.4	0.16	0.3	0.15	0.13	0.06	0.18	0.14	0.04	0.010	0.03			
Mean 95% c.l.	0.3	0.11	0.3	0.09	0.09	0.04	0.13	0.09	0.02	0.007	0.02			

[a] For Dhofar 025 and Yamato 82192, the results are means weighted according to the mass of the two splits of Table 2. "Stnd. Dev." is the sample standard deviation of the 98 analyzed spots, based on means of individual beads. "Mean 95% c.l." is the mean of the 95% confidence limits for each sample. *Mg′* is mole percent Mg/(Mg + Fe). "Mass" is the total mass of material, in miligrams ground to make fused beads.

Presumably as a result of contamination, all three of our subsamples have concentrations of Au that are large compared to feldspathic lunar meteorites from cold deserts with similar Ni and Ir concentrations (Fig. 2). A characteristic, and thus far unique, feature of Dhofar 025 among lunar meteorites is the presence of vugs containing celestite ($SrSO_4$) from terrestrial alteration, which lead to Sr concentrations that are more than 10 times greater than those of feldspathic samples from the Apollo collection (Fig. 3a). Ba is also enriched, but to a smaller degree (Fig. 3b).

The compositional variation (INAA) among our 13 subsamples of NWA 482 is small and comparable to that of MAC 88104/5 (Jolliff et al., 1991a). For example, the relative standard deviations for Sc and Sm in our subsamples of NWA 482 are only 6 and 7%, respectively (Table 2). The compositional variation among subsamples of NWA 482 is systematic, however, and consistent with minor variation in the ratio of plagioclase (low concentrations of Fe, Sc, Sm, Th) to mafic minerals (higher concentrations; Fig. 4). Of the four hot-desert meteorites analyzed here, NWA 482 appears to be the only one not enriched in Ba as a result of terrestrial alteration (Fig. 3a)

4. DISCUSSION

4.1. Some Apollo and Luna Regolith Background

Here we provide a brief discussion of some first-order geochemical characteristics of regolith samples ($<$1-mm fines or "soils") from the Apollo and Luna missions as a framework for subsequent discussion of lunar meteorites, most of which are breccias composed of regolith.

Regoliths (and most polymict samples) from the Apollo and Luna missions are mainly mixtures of components from three geochemical provinces: (1) Fe- and Th-poor feldspathic material of the highlands, (2) Fe-rich basalt and pyroclastic glass from the volcanic maria, and (3) materials having intermediate concentrations of Fe but high concentrations of K, REE (rare earth elements), P, Th and other incompatible elements. Such Th-rich materials are usually identified by the pseudochemical term KREEP, but, lithologically, most are impact-melt breccias and impact-melt glass. In terms of the terrane concept of Jolliff et al. (2000) and Haskin et al. (2000), we can equate the feldspathic geochemical province with the Feldspathic Highlands Terrane. Similarly, much, if not most (Haskin et al., 2000), of the Th-rich material in Apollo regoliths originates from the Procellarum KREEP Terrane, the high-Th region of the lunar crust (Fig. 5) identified as unusual by the Apollo orbiting gamma-ray spectrometers (Metzger et al., 1973) and unique by the Lunar Prospector gamma-ray spectrometer (Lawrence et al., 1998, 2000; Jolliff et al., 2000). Mare volcanics occur in both terranes. Other lithologies, such as alkali anorthosite, felsite, norite, and troctolite, are volumetrically minor in Apollo regoliths and, for the purposes of this discussion, can be considered as subcomponents of the KREEP or feldspathic components.

As a consequence of the ternary mixing relationship, on two-element plots involving a major element and an incompatible element (e.g., Fig. 6), regolith compositions inscribe a triangle defined by the compositions of the three components: KREEP-rich materials, feldspathic materials, and mare volcanics. For any given regolith sample, however, the lithologies representing the three components do not necessarily plot exactly at the apices of the triangle of Figure 6, but somewhere within the gray fields of Figure 6a, because the lithologies vary in identity and composition from site to site. Although, historically, KREEP-rich rocks have been regarded as a form of highland material, there is no particular advantage to or justification for this association (Korotev and Gillis, 2001). Geochemically and geographically, KREEP-rich rocks represent a distinct province, one no more akin to the feldspathic highlands than to the maria. The ternary nature of Apollo regolith compositions has been recognized since the time of the Apollo missions (Goles et al., 1971; Meyer et al., 1971; Schonfeld and Meyer, 1972; Duncan et al., 1973; Schonfeld, 1974), although lithologies and representative compositions associated with each of the three components have changed with time.

Samples of Apollo and Luna regoliths cover much of the range of the mixing diagram depicted in Figure 6a. The regolith of Apollo 14 derives mainly from Th-rich impact-melt breccias and rocks (Jolliff et al., 1991b) and thus plots near the KREEP apex of Figure 6. The Luna 24 regolith and the most iron-rich regoliths of Apollo 15 and 17 are composed mainly of mare basalt and volcanic glass, so these regoliths plot near the mare apex of the triangle. Apollo 12 regolith samples are mainly binary mixtures of mare basalts and KREEP impact-melt breccias similar to those of Apollo 14, so they plot along the KREEP-mare side of the triangle. Apollo 16 regoliths plot closest to the feldspathic highlands apex because they are dominated by FeO- and Th-poor material of the Feldspathic

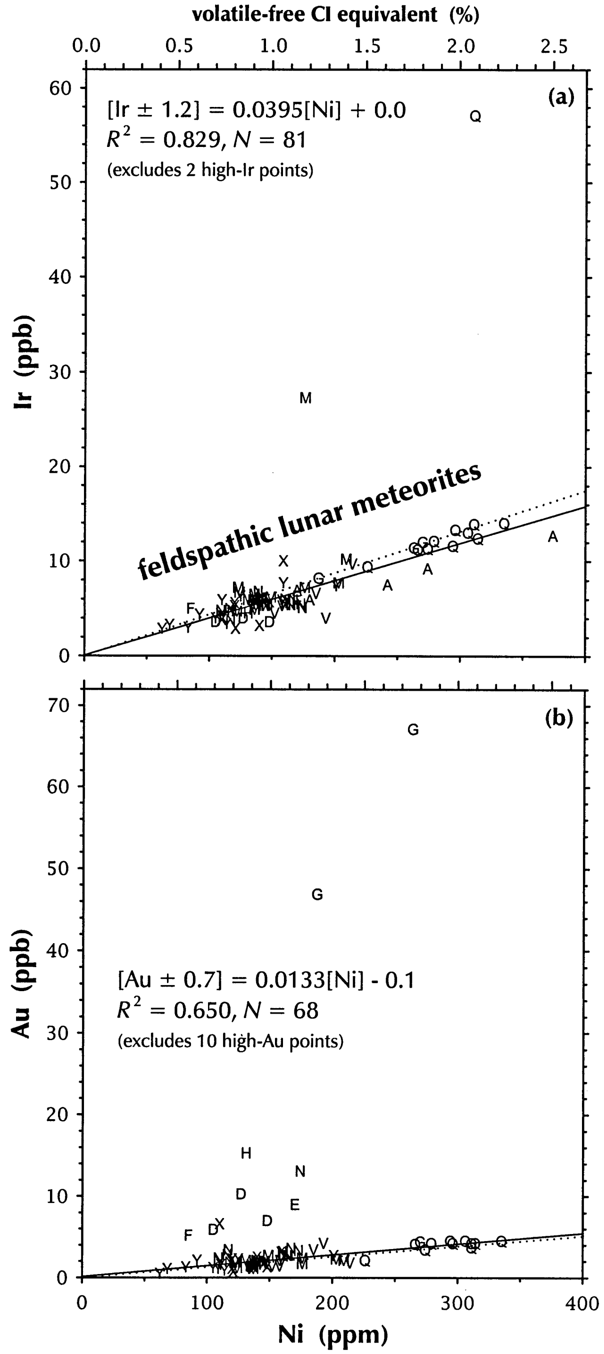

Fig. 2. Variation of Ir and Au with Ni among subsamples of feldspathic lunar meteorites. The solid lines are simple least-squares fits to those points that are not highly anomalous; the equation of the lines are given in the figure. The dotted lines are defined by the origin and the point (off scale) representing CI chondrites (Anders and Grevesse, 1989). (a) For Ir, the two anomalous points are for subsamples of Antarctic meteorites (M = MAC88105 and Q = QUE93069; Jolliff et al., 1991a; Korotev et al., 1996) and probably are not the result of terrestrial contamination but of some highly refractory extraterrestrial component in the small breccia subsamples. (b) For Au, all the anomalous points except one (X) are for hot-desert meteorites (G = DaG 262, H = DaG 400, D = Dhofar 025, F = Dhofar 081, X = Yamato 82192; the key to other symbols is in Table 1). The figure shows that the extralunar component of the feldspathic lunar meteorites is consistent with CI-chondrites, at least with respect to Ir/Ni and Au/Ni ratios,

Fig. 2 (continued). and that the feldspathic lunar meteorites contain the equivalent of 0.5 to 2% chondritic material. Most data in the figure are from this laboratory (Korotev et al., 1983, 1996; Lindstrom et al., 1986, 1987; Jolliff et al., 1991; this work), although data of Bischoff et al. (1987, 1998), Fukuoka et al. (1986a), Koeberl (1988), Taylor et al. (2001a), Warren and Kallemeyn (1991b), and Warren et al. (2001) are included for those lunar meteorites for which we have little or no data (DaG 262, Dhofar 026 and 081, and Yamato 82192/3).

Highlands Terrane. However, they also contain significant proportions of lithologies representing the other two apices of the triangle. The mature (i.e., well mixed) regolith that is typical of the surface of the Apollo 16 site contains 25 to 29% KREEP-bearing impact-melt breccias and ~6% mare volcanic material (Korotev, 1997; Zeigler et al., 2003), so it has a greater concentration of Th and other incompatible elements and a greater concentration of FeO than the feldspathic apex of the triangle. Similarly, those regoliths of Apollo 15 and 17 that are least contaminated with mare volcanics (lowest FeO) are mixtures of feldspathic highlands materials and KREEP-bearing melt breccias (Korotev, 1987, Jolliff et al., 1996).

In large part because (1) all of the Apollo sites lie in or near the Procellarum KREEP Terrane (Fig. 5) and (2) the several large impacts, culminating with the Imbrium impact, occurred in the Procellarum KREEP Terrane and spread Th-rich ejecta over the lunar surface (Haskin, 1998; Haskin et al., 1998), the regoliths of all Apollo landing sites contain Th-rich impact-melt breccias. Thus, nearly all Apollo soil samples contain $>$ 1 ppm Th. Even the mare-basalt-dominated regolith of Apollo 11 contains ~9% Th-rich impact-melt breccias (Korotev and Gillis, 2001). Regolith samples from the Apollo 12, 15, and 17 sites have a considerable range in compositions because the sites are geologically complex, which leads to variable proportions of the three components from place to place at each site. At those sites, however, even regoliths with the least mare component contain $\geq$ 2.5 ppm Th because of the large proportion of KREEP-bearing material at the sites. Some immature regolith samples from Apollo 16 contain much less that the 25 to 29% KREEP-bearing impact-melt breccia of the typical regolith and thus have low concentrations of Th. Such samples occur as layers in cores (Korotev, 1991) and in the ejecta of North Ray Crater (Jolliff and Haskin, 1995; Korotev, 1996). Unlike the feldspathic lunar meteorites of similar composition, all Th-poor regoliths of Apollo 16 are immature (poorly mixed) and dominated by coarse fragments derived from a single subsurface block of anorthosite or feldspathic breccia.

4.2. Some Lunar Meteorite Basics

4.2.1. New Hot-Desert Meteorites

More than half of the known lunar meteorites have been discovered since 1997 in the deserts of Oman and northwestern Africa (Table 1). Nearly all of the available data on these new meteorites are preliminary in that they are available only in abstracts. For several of the most recently discovered lunar meteorites, there are few or no data on composition or cosmic-ray exposure. Compared to Apollo lunar samples, all hot-desert meteorites for which there are chemical data are contaminated,

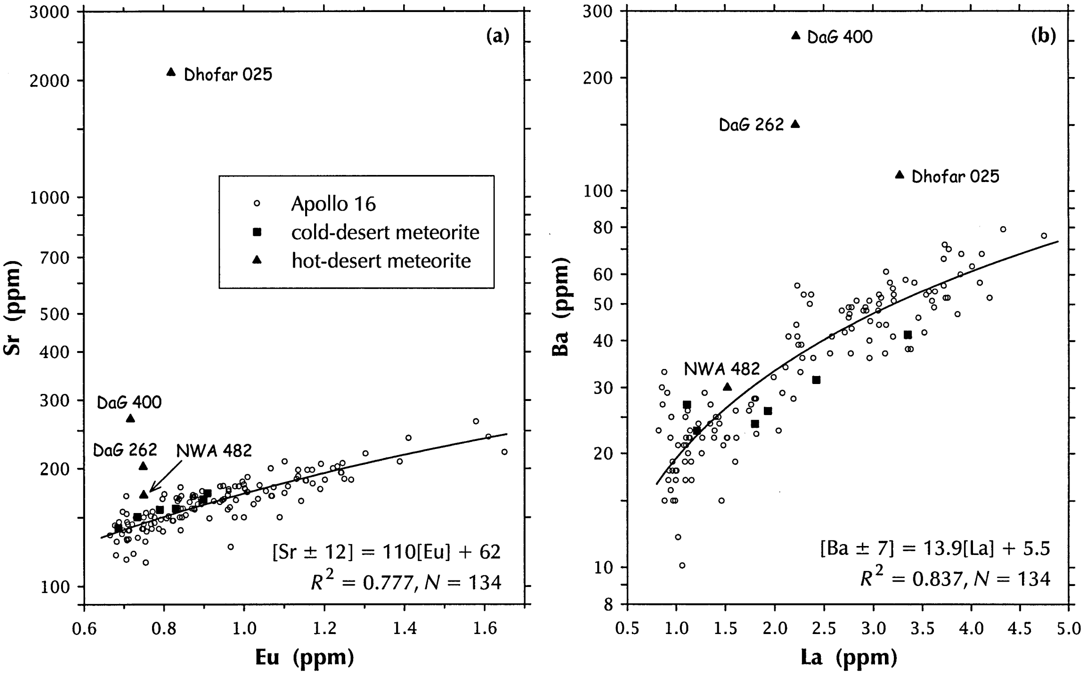

Fig. 3. Among Apollo 16 samples with compositions similar to the feldspathic lunar meteorites (small circles), Sr correlates with Eu and Ba correlates with La. The curved regression lines are linear on linear plots. The plots shows that (1) feldspathic, cold-desert meteorites have Sr and Ba concentrations expected on the basis of their REE concentrations and (2) the feldspathic, hot-desert meteorites analyzed here are all enriched in Sr and, except for NWA 482, Ba to varying degrees, as a result of terrestrial alteration. Among the cold-desert meteorites, the two points with greatest Sr and Eu concentrations correspond to paired samples Yamato 82192/3 and Yamato 86032. A plot similar to (a) with Na instead of Eu (not shown) suggests that Na concentrations have not been modified in the hot-desert meteorites. On the basis on literature data, all hot-desert meteorites are also enriched in K, and the degree of K enrichment correlates with the degree of Ba enrichment, although the relative magnitude of the Ba enrichment is not as great for K. All data are from this laboratory (meteorites: this work; Korotev et al., 1983, 1996; Jolliff et al., 1991a, Lindstrom et al., 1991a; Apollo 16: this work and Jolliff and Haskin, 1995).

to varying degrees, with elements associated with terrestrial aqueous alteration (alkali and alkaline earth elements, Br) and, typically, gold (section 3).

Many of the lunar meteorites that have been collected and acquired by private collectors in hot deserts have been first described and classified by those having little experience with the Apollo collection. As a consequence, there are some inconsistencies in the preliminary literature, particularly with regard to breccia type. Compounding the problem is the heterogeneous nature of lunar breccias and the small size of subsamples upon which classifications have been based. For example, DaG 400 has been described as an impact-melt breccia (Bukovanska et al., 1999) and a regolith breccia containing clasts of impact-melt breccia (Zipfel et al., 1998; Cohen et al., 1999; Semenkova et al., 2000). Although we have not studied a thin section of the meteorite, we have examined a large slab. The rock appears to be a regolith breccia containing clasts of impact-melt breccia, one of which is several centimeters in longest dimension (Fig. 7).

4.2.2. *How Many Meteorites and How Many Craters?*

At this writing we are aware of 48 stones, each with a unique alphanumeric designation, that are recognized to be meteorites from the Moon (Table 1). When unambiguous or suspected cases of terrestrial pairing are considered, the number of known objects that made the Moon to Earth trip decreases to ~26 (Table 1). Other cases of terrestrial pairing may yet be found among recently discovered meteorites, especially the many (*N* = 22) Dhofar stones (Nazarov et al., 2002, 2003; Russell et al., 2002, 2003) so the number of lunar meteorites might be < 26 but probably not < ~22.

For the purpose of using lunar meteorites to learn about the Moon it is important to know how many different locations on the Moon they represent. Is it 1, 26, or some value in between? When only two lunar meteorites were known, it was easy to argue that both were probably launched from the same crater by one impact (e.g., Lindstrom et al., 1986). Now that there are many, the range of cosmic-ray exposure ages clearly demonstrates that the meteorites derive from multiple impacts. As a persuasive tool it would be effective to present an up-to-date table or figure summarizing ejection or launch ages, such as those of Nishiizumi et al. (1996), Polnau and Eugster (1998), or Arai and Warren (1999). We do not present such a summary because data for the newest meteorites are not yet available and many of the reported data are described as preliminary. Although the exact number of impacts producing the lunar meteorites is not known, we conclude here, on the basis of available cosmic-ray exposure data and compositional arguments

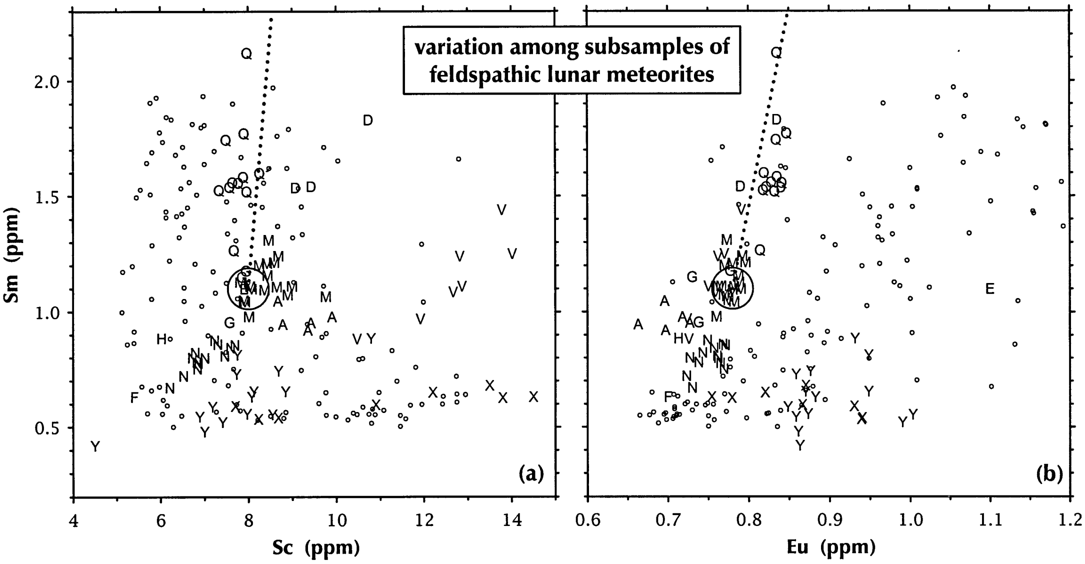

Fig. 4. Variation of Sm with Sc and Eu among subsamples of feldspathic lunar meteorites (letter symbols; see Table 1 for complete key) and comparison to Apollo 16 samples of similar composition (small circles). (a) The Sc-rich meteorites (X and Y: Yamato 82192 and 82193 and V: Yamato: 791197) contain a substantial (~5–10%) component of mare volcanic material. The most Sc-poor subsamples of Yamato 82192/3 overlap in composition with Yamato 86032, with which it is paired. (b) Yamato 82/86 is compositionally distinct in being anomalously rich in Eu (also Sr and Na) compared to other feldspathic lunar meteorites, although many Apollo 16 samples are similar in this regard. The high Eu concentration of Dhofar 026 (E; Taylor et al., 2001a) is suspicious because there is a strong correlation between Eu and Na in feldspathic lunar materials (Korotev et al., 2003) and the meteorite is not correspondingly enriched in Na. In both plots, the large circle is the estimate of the mean composition of the feldspathic upper crust, as derived from the meteorites (Table 5). The dotted line is a mixing line between feldspathic upper crust and KREEP-rich impact-melt breccias of the Apollo sites (Korotev, 2000). It is not known if the high Sm concentrations of QUE 93069 (Q) and Dhofar 025 (D) are caused by a discrete component of some form of KREEP or whether they simply reflect natural variation (more or less trapped melt) in early feldspathic rocks of the highlands. See Figure 2 for sources of data.

presented below, which are largely an extension of those presented by Warren (1994), that the number of source craters is a large fraction of the number of meteorites.

There are two reasonably well established cases of source-crater or launch pairing, that is, meteorites found too far apart on Earth to be fragments of a single bolide that broke apart upon encountering the Earth's atmosphere or surface, but which are similar enough in composition, mineralogy, and launch age to have likely been ejected from the Moon by a single impact (Warren, 1994). One such case is the "YA" meteorites, Yamato 793169 and Asuka 881757; both are mare basalts (Warren and Kallemeyn, 1993; Jolliff et al., 1993; Thalmann et al., 1996). The other is the "YQ" meteorites, paired stones Yamato 79/98 (793274/981031) and QUE 94281; all are breccias consisting of subequal amounts of mare and highlands material (Arai and Warren, 1999; Lorenzetti and Eugster, 2002; Arai et al., 2002; Korotev et al., 2003; Fig. 1a). We strongly suspect that EET87/96 is also launch paired with the YQ meteorites because of textural, lithologic, and compositional similarities as well as overlap in cosmic-ray exposure parameters (Korotev et al., 2003). Thus, we conclude that the upper limit on the number of locations on the lunar surface from which the lunar meteorites derive is 23 (i.e., the 26 entries of Table 1 minus 3).

Two earlier estimates of the lower limit for the number of source craters, based mainly on estimates of launch age obtained from cosmic-ray exposure data, are 12 (data for 18 of the 48 stones; Nishiizumi et al., 1999) and 8 (data for 15 stones; Polnau and Eugster, 1998). As noted in the "Introduction," launch ages for lunar meteorite range from too short to measure accurately, such as < 0.07 Ma for EET 87521 (Nishiizumi et al., 1996), to 10 Ma for Yamato 82/86 (i.e., the paired stones Yamato 82912, 82193, and 86032; Eugster et al., 1989; Vogt et al., 1991). Five to eight of the lunar meteorites were launched in the past 0.1 Ma (e.g., summaries of Nishiizumi et al., 1996; Polnau and Eugster, 1998; and Arai and Warren, 1999). Uncertainties in the individual ages of the recently launched meteorites all mutually overlap. Thus, the most conservative estimate for the minimum number of launch craters assumes that all recently ejected meteorites were launched by a single impact (Yamato 79/98, QUE 94281, and EET87/96 are among these). As noted by Arai and Warren (1999), however, on the basis of the work of Gladman et al. (1996), most material ejected from the Moon strikes the Earth sooner rather than later. Thus, we would expect a greater number of young launch ages than old ones. It is therefore unlikely that the numerous recently launched lunar meteorites, which include both low-FeO and high-FeO stones (Fig. 1a), all derive from one crater.

If we assume that (1) Asuka 881757 and Yamato 793169 are launch paired, (2) Yamato 79/98, QUE 94281, and EET 87/96 are launch paired, (3) Yamato 983885 is launch paired with Calcalong Creek, (4) every Dhofar > 301 meteorite is terrestrially paired with one of the Dhofar < 300 meteorites (i.e., there are only four Dhofar meteorites, represented by 025, 026, 081, and 287), (5) the recently announced DaG 996 is paired with either DaG 262 or DaG 400, and (6) none of the remaining

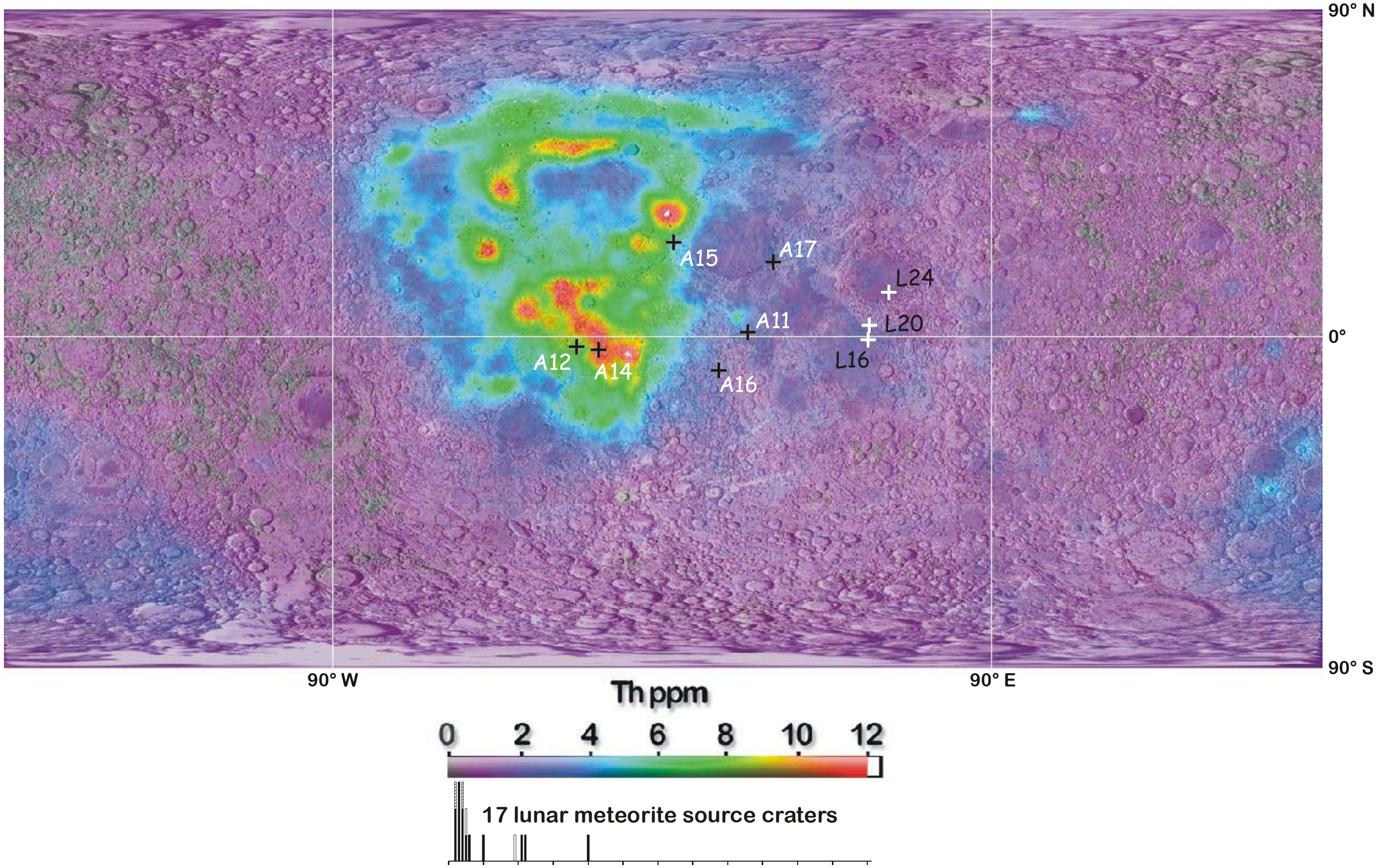

Fig. 5. Shaded relief map of the whole Moon (simple cylindrical projection) overlain with distribution of surface concentrations of thorium. The area between the vertical lines (90°W and 90°E) represents the nearside and the locations of the six Apollo (A) and three Luna (L) sampling sites are shown. Because the figure compares global Th concentrations derived from the Lunar Prospector gamma-ray spectrometer data (Lawrence et al., 2000) to concentrations obtained from samples, we use the Gillis et al. (2000) ground-truth recalibration of the Lawrence et al. (2002) Th data. At low Th concentration the values of Lawrence et al. (2000) are unrealistically high compared to samples (Fig. 13b). The histogram of Figure 13a is reproduced below the legend. Jolliff et al. (2002) define the Procellarum KREEP Terrane as the entire area within the smallest polygon that can be drawn that includes all pixels with >3.5 ppm Th. The map shows that (1) all of the Apollo landing sites are in or near the Procellarum KREEP Terrane (Jolliff et al., 2000) and (2) most of the brecciated lunar meteorites likely derive from violet and gray regions of the map. The recalibration of Gillis et al. (2000) assumes that the average Th concentration of the vast northern farside surface and the feldspathic lunar meteorites are the same, on average. On the basis of this calibration, 84% of the Moon's surface has < 3 ppm Th. The blue area in the interior of the high-Th region northwest of the Apollo 15 site are the basalts of the Imbrium impact basin.

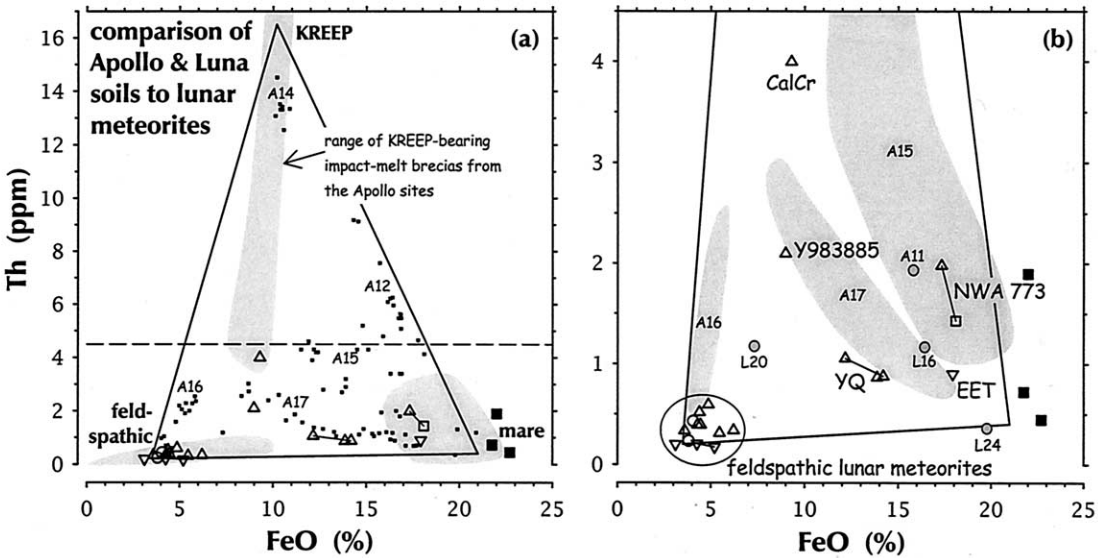

Fig. 6. (a) Regolith samples (<1-mm fines) from the Apollo and Luna missions (small points) consist mainly of three compositionally distinct types of material represented by the apices of the triangle: basalt and volcanic glass from the maria, feldspathic rocks of the highlands, and Th-rich impact-melt breccias and glass often identified as KREEP. The gray fields represent the compositional range of these three classes of materials among Apollo samples. The lunar meteorites are represented by the large points (key in Table 1). The three lunar meteorites with > 20% FeO (filled squares) are mare basalts (no Th data are available for Dhofar 287); the others are mainly regolith and fragmental breccias (Table 1) and, thus, are comparable to the Apollo and Luna regoliths. (b) Expansion of lower portion of (a), with the range of soil compositions indicated by the gray fields or circles. The Apollo 15 and 17 sites were at a mare-highlands boundary, so soil compositions vary considerably (many samples over several kilometers of traverses). Soils of Apollo 11 and the three Russian Luna sites (L16, L20, and L24) are each represented by a single point because the samples were collected at a single location on each mission. Most lunar meteorites are feldspathic. A few are mixtures of material of both the maria and feldspathic highlands (YQ: Yamato 793274/981031 and QUE 94281; EET: EET 87521/96008). Only Calcalong Creek, and possibly Yamato 983885 and Northwest Africa 773, appear to contain any significant KREEP material (also, most notably, Sayh al Uhaymir 169, which plots far off scale at 33 ppm Th).

feldspathic lunar meteorites (all Antarctic) are launch paired with another, then the lower limit on the number of source craters is 18. Some launch pairs among the recently launched feldspathic lunar meteorites are allowed by the cosmic-ray exposure data (e.g., ALHA 81005, Yamato 791197, and QUE 93069/94269; Nishiizumi et al., 1996; Polnau and Eugster, 1998), but on the basis of the compositional data reviewed below, there are no strong reasons to believe that any of these meteorites are related other than the fact that they all derive from the lunar highlands. The assumption that Yamato 983885 is launch paired with Calcalong Creek is tentative and based on the similarities noted in the next section. Cosmic-ray exposure data for Yamato 983885 are not yet available.

4.2.3. *Lithologic and Compositional Diversity*

Most lunar meteorites are regolith or fragmental breccias consisting of lithified (shock compacted but largely unmelted), fine-grained (micrometer to centimeter) material from the upper few meters of the Moon (e.g., Warren, 2001). Regolith breccias differ from fragmental breccias mainly in containing lithologies such as agglutinates and glass spherules that can only be created at or above the surface of the Moon (Stöffler et al., 1980). Also, fragmental breccias do not have a glassy matrix, although some regolith breccias do. Regolith breccias tend to have high concentrations of trapped solar wind gases (Fig. 8), comparable to levels observed among Apollo soils because much of the material from which they are formed was exposed at the lunar surface as fine grains (Bogard and Johnson, 1983; McKay et al., 1986). In the fragmental breccias, agglutinates and glass spherules are rare to absent and concentrations of trapped solar-wind gases are less than in regolith breccias, but still much greater than in unbrecciated rocks (Fig. 8). With respect to regolith and fragmental breccias from Apollo 16, McKay et al. (1986) suggested that "the two breccia types are contemporaneous and represent different zones of a megaregolith." Among lunar meteorites, fragmental breccias probably consist of material from deeper in the regolith (meters to tens of meters?), on average, than regolith breccias.

A few lunar meteorites have been classified as impact-melt breccias and at least one, Dhofar 026, is a granulitic breccia (James et al., 2003). Most impact-melt breccias consist of "rock and mineral clasts embedded in an *igneous-textured* crystalline *matrix*" of solidified impact melt (Stöffler et al., 1980). In order for impact melt to crystallize, it has to cool slowly, which requires a crater of at least several kilometers in diameter (e.g., Deutsch and Stöffler, 1987). The ratio of the volume of melt to the volume of the crater increases with crater size (Cintala and Grieve, 1998), however, so it is likely that most impact-melt breccias were formed in craters larger than a few kilometers in diameter. On this basis Warren (1996) reasoned that most impact-melt breccias at the surface of the Moon are, in fact,

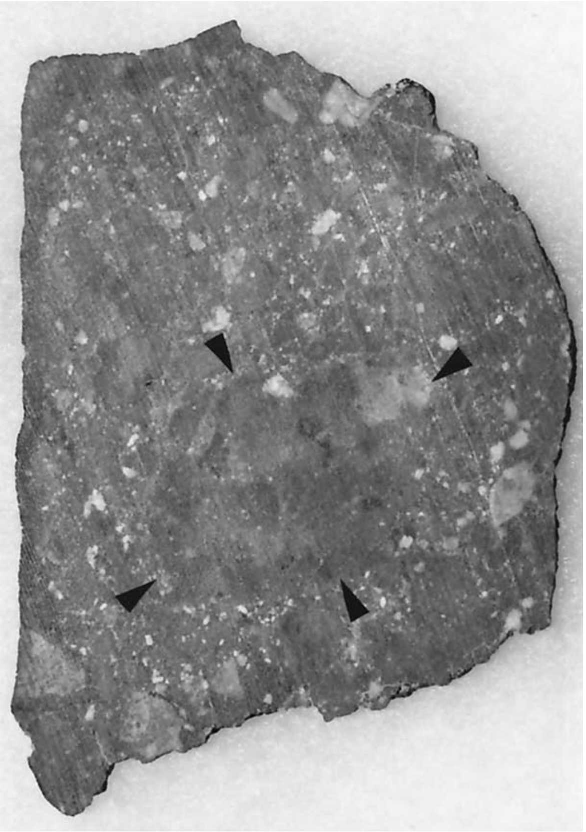

Fig. 7. Photograph of a sawn slab of Dar al Gani 400. The longest dimension is ~9 cm. The meteorite is a regolith breccia with clasts of impact-melt breccia (Zipfel et al., 1998; Cohen et al., 1999; Semenkova et al., 2000). What appears to be a single large melt-breccia clast is delineated by the arrows.

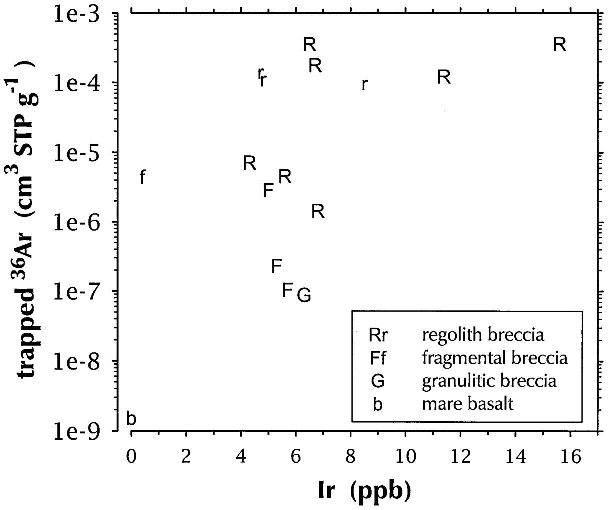

Fig. 8. Variation of the concentration of trapped solar-wind ^{36}Ar with the concentrations of Ir among lunar meteorites. Upper-case letters represent feldspathic lunar meteorites (>25% Al_2O_3) and lower-case letters represent meteorites with a substantial component of mare-derived material (<22% Al_2O_3). All meteorites with high ^{36}Ar are regolith breccias (R and r). The figure shows that lunar meteorites that have high abundances of trapped solar wind tend to also have high concentrations of siderophile elements, probably from micrometeorites. Noble gas data are not yet available for any of the impact-melt breccias. Although the "b" point is specifically for Asuka 881757, a mare basalt, the point represents all igneous and plutonic rocks of the lunar crust in that all such rocks have essentially zero concentrations of Ir and trapped solar wind nuclides compared to brecciated materials. Noble gas data from Bischoff et al. (1987), Bogard and Johnson (1983), Eugster and Niedermann (1988), Eugster et al. (1986, 1989, 1991, 1996, 2000), Greshake et al. (2001), Nagao and Miura (1993), Ostertag et al. (1986), Palme et al. (1991), Polnau and Eugster (1998), Scherer et al. (1998), Shukolyukov et al. (2001), Swindle et al. (1995), Takaoka (1986), and Thalmann et al. (1996). Ir data are from the references in Table 1.

splash ejecta from basin-forming impacts. Regardless, a given impact-melt breccia likely represents a large volume of lunar crust. Granulitic breccias, which are discussed in more detail in section 4.5, are rocks that have been thermally metamorphosed by the heat of large impacts such that solid state recrystallization has occurred (James and Hammarstrom, 1977; Stöffler et al., 1980).

Before discussing the feldspathic lunar meteorites, a brief review of the nonfeldspathic meteorites is required to put the feldspathic meteorites in context. The discussion begins at the high-FeO end of the trend of Figure 1a and progresses to the low-FeO end.

Four lunar meteorites are basalts from the maria. With 2 to 3% TiO_2 (Table 1), all four are low-Ti basalts in the classification system adopted for Apollo mare basalts (e.g., Papike et al., 1998). (Crystalline mare basalts of the Apollo and Luna collection range from ~1 to 12% TiO_2.) As noted above, Yamato 793169 and Asuka 881757 are likely from the same source crater. It is unlikely that NWA 032 derives from the same source crater as the YA meteorites, however, because there are significant differences in composition, mineralogy, Moon to Earth transit time, and crystallization age (Misawa et al., 1992; Warren and Kallemeyn, 1993; Jolliff et al., 1993; Thalmann et al., 1996; Nishiizumi and Caffee, 2001; Fagan et al., 2002; Korotev et al., 2003). Preliminary compositional and petrographic data on Dhofar 287, which contains a minor portion of regolith breccia, do not suggest that the meteorite has any relationship to the other three basaltic lunar meteorites (Taylor et al., 2001b; Anand et al., 2002; Demidova et al., 2002; Shih et al., 2002).

The two brecciated lunar meteorites of mare composition, EET 87/96 and NWA 773, are similar in some respects. Both are breccias consisting mainly of very-low-Ti (<1% TiO_2) basalt or gabbro and each contains coarse grains of finely exsolved pyroxene, suggesting that the parent magmas cooled more slowly than that of most Apollo mare basalts (Delaney, 1989; Warren and Kallemeyn, 1989; Takeda et al., 1992; Arai, 2001; Warren and Ulff-Møller, 1999; Korotev et al., 2002a). NWA 773 contains clasts of a unique olivine gabbro cumulate (Fagan et al., 2001; Korotev et al., 2002a; Jolliff et al., 2003), however, that has not been reported in EET 87/96 (Delaney, 1989; Warren and Kallemeyn, 1989; Arai, 2001; Mikouchi, 1999; Warren and Ulff-Møller, 1999). Cosmic-ray exposure data are not yet available for NWA 773, so launch pairing with EET 87/96 cannot be dismissed. Arai et al. (1996) and Arai and Warren (1999) classify EET 87521 as a fragmental breccia, but on the basis of the description of Mikouchi (1999), it is marginally a regolith breccia.

The four "mixed" meteorites of Table 1 and Figure 1 contain feldspathic material and mare volcanic material in subequal abundances. Of these, as noted above, Yamato 79/98 and QUE 94281 are almost certainly launch paired. Few data are available for Yamato 983885, but based on the major-element composition and petrographic description of Kaiden and Kojima (2002) and our own unpublished INAA data (Figs. 1 and 6), the meteorite is similar to Calcalong Creek (Hill et al., 1991, 1995; Marvin and Holmberg, 1992), so the two meteorites may be launch paired. Calcalong Creek has moderately high concentrations of incompatible elements (e.g., 4 ppm Th), similar to soil from the Apollo 15 site on the edge of the Imbrium basin (Fig. 6) and consistent with other locations in or near the Procellarum KREEP Terrane (Fig. 5). Incompatible-element concentrations in Yamato 983885 are only half those of the Calcalong Creek stone, but are still greater than those any of the feldspathic lunar meteorites.

With 33 ppm Th, the recently announced Sayh al Uhaymir 169 (Russell et al., 2003) must originate from the Procellarum KREEP Terrane. The meteorite is an impact-melt breccia with attached regolith breccia. On the basis of preliminary data (Gnos et al., 2003) the meteorite appears to be very similar to some impact melt breccias and regolith breccias from the Apollo 12 and 14 sites (e.g., Jolliff et al., 1991b; Korotev et al., 2002b).

4.2.4. *Compositional Systematics*

Most (>98%) of the crystalline material of the lunar crust consists of only four minerals: plagioclase, olivine, pyroxene (both clino- and ortho-), and ilmenite (and, in mare basalts, other Fe-Ti oxides). As a consequence, on a plot of Al_2O_3 vs. FeO, lunar rocks necessarily plot between the composition of plagioclase (high Al_2O_3, low FeO) and the compositions of the three Fe-bearing minerals (high Fe, low Al_2O_3; Fig. 1). Among polymict samples (breccias, glasses, regoliths), the average concentrations of Al_2O_3 and FeO in the plagioclase and the average concentrations of Al_2O_3 and FeO in the Fe-bearing minerals do not vary greatly, thus polymict samples define a nearly linear trend between the averages. The trend is not truly linear for several reasons. As noted above, in terms of lithologic components the system is ternary (Fig. 6), not binary. The average Al_2O_3 concentration of plagioclase and the average FeO concentration of the iron-bearing minerals differ among the three components. These parameters, in turn, depend upon anorthite content of plagioclase, Ca and Al content of pyroxene, Mg/Fe ratio of pyroxenes and olivine, pyroxene to olivine ratio, etc. Despite these nuances, the trend is remarkably linear. Lunar meteorites tend to plot on the trend of the Apollo and Luna soils of Figure 1, and their positions along the trend (e.g., FeO or Al_2O_3 concentration) serves as a useful first-order compositional classification parameter in the way that SiO_2 concentration is used with terrestrial igneous rocks.

4.3. Feldspathic Lunar Meteorites

Most brecciated lunar meteorites are feldspathic in that plagioclase feldspar is the dominant mineral phase. Concentrations of Al_2O_3 among the feldspathic lunar meteorites range from 26 to 31% (Table 1; Fig. 1), leading to normative plagioclase abundances of 72 to 86 mass% or ~76 to 89 vol.%. The normative anorthite content of the plagioclase averages 95 to 97%, and pyroxene (predominantly low-Ca) dominates over olivine. If they were plutonic rocks, nearly all of the feldspathic lunar meteorites would be classified as noritic anorthosites, with the most mafic (Fe- and Mg-rich, Al-poor) ones being anorthositic norites (Stöffler et al., 1980). All feldspathic lunar meteorites have low concentrations of incompatible elements, indicating that all are largely free of the KREEP component that is characteristic of soils from the Apollo sites (Fig. 6). For example, among the eleven feldspathic lunar meteorites for which there are data, mean concentrations of Sm and Th span the narrow ranges of 0.6 to 1.6 ppm Sm and 0.2 to 0.6 ppm Th (Figs. 4 and 6). This range is below that of all but a few anomalous regolith samples from Apollo 16 (section 4.1).

The feldspathic lithologic components of feldspathic lunar meteorites are largely similar to those of the Apollo 16 regolith. Also, as with the Apollo 16 regolith, volcanic material from the maria has been found in most of the well-studied feldspathic lunar meteorites. The main differences are that (1) the Apollo 16 regolith contains a significant proportion of moderately mafic (~10% FeO) impact-melt breccias that have high concentrations of incompatible elements while such breccias are minor to absent in the meteorites and (2) the feldspathic rocks of the Apollo 16 regolith are more feldspathic (greater average Al_2O_3 concentration) than those of the feldspathic lunar meteorites (Fig. 1b). The former difference results from the proximity of the Apollo 16 site to the Procellarum KREEP Terrane (Fig. 5). The latter difference results from the large proportion of highly feldspathic ferroan anorthosite (>95% plagioclase, e.g., Warren, 1990) in the Apollo 16 regolith (Korotev, 1997), which, in turn, is likely a reflection of the global observation that some regions of the lunar surface are more feldspathic than others (Hawke et al., 2003).

4.3.1. *Comparison of Compositions*

Discounting the recently announced Dhofar meteorites (i.e., Dhofars > 300; Nazarov et al., 2002; Takeda et al., 2003; Russell et al., 2002, 2003), for which few data are available and pairing relationships with the other Dhofar lunar meteorites have not been established, there are eleven feldspathic lunar meteorites. Although all are similar in being rich in plagioclase feldspar and poor in incompatible elements, compositional differences exist among them. Given that the meteorites are all breccias, these differences reflect the heterogeneity of the surface of the lunar highlands.

For those elements not affected by terrestrial alteration, DaG 262, followed closely by MAC 88104/5, is the most typical feldspathic lunar meteorite in that it has a composition closest to the mean of all of them. (This and other generalizations made here are based on data from the references of Table 1.) The first lunar meteorite to be recognized, ALHA 81005, remains the most mafic of those feldspathic lunar meteorites that contain a negligible proportion of mare-derived material; at the other extreme are Dhofar 081, Dhofar 026, DaG 400, and NWA 482 (Fig. 9). Yamato 791197 is also at the mafic extreme, but it contains clasts of mare derivation (Goodrich and Keil, 1987; Warren, 1994). Among the feldspathic lunar meteorites, Yamato 791197 appears to contain the greatest proportion of mare

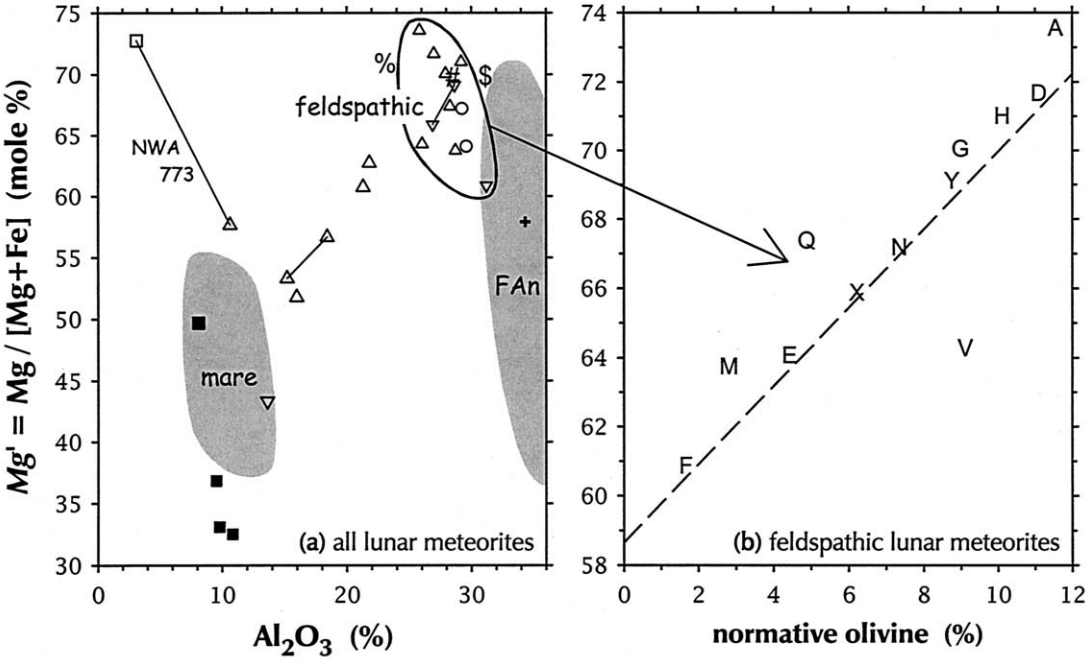

Fig. 9. (a) Variation of *Mg′* with Al_2O_3 in lunar meteorites (geometric symbols, key in Fig. 1a). For this plot, *Mg′* represents whole-rock mole percent Mg/[Mg + Fe], but with Mg and Fe normalized to a chondrite-free basis using the Ir concentration of the meteorites (this correction raises *Mg′* by ~1 unit, on average, over the measured value). Symbols connected by a line represent extreme compositions within a single meteorite (regolith breccia and olivine gabbro portions of NWA 773, Yamato 793274/981031, and Yamato 82 and Yamato 86 portions of paired stones Yamato 82192/3 and 86032). The gray field at low Al_2O_3 represents the range of crystalline mare basalts from the Apollo and Luna missions. The gray field at high Al_2O_3 represents the range of ferroan anorthosites, with "+" symbol representing the mean (whole rock, >90% plagioclase; samples and references of Table 12 from Papike et al., 1998). The feldspathic lunar meteorites are more magnesian than the mare meteorites and, on average, ferroan anorthosites. The keyboard symbols represent the mean of five estimates ($) of the pre-Imbrium components of the Apollo 16 regolith (Fig. 1b), the feldspathic upper crust estimate (#) of Table 5 derived from the feldspathic lunar meteorites, and the Luna 20 regolith (% = meteorite free to be consistent with $ and #). All have similar *Mg′* of ~70. (b) Among feldspathic lunar meteorites, *Mg′* is variable and increases with the mass fraction of normative olivine. The dashed line represents a simple least-squares fit to the data ($R^2 = 0.97$, $Mg' = 1.13[NO] + 59$), excluding data for Yamato 791197. Yamato 791197 lies off the line because a significant fraction of the Fe and Mg derives from mare volcanics (Warren, 1994; Korotev et al., 1996), which have lower *Mg′* (a).

volcanic material in that it has the greatest concentrations of elements associated with mare basalt (Sc, Ti, V, Mn, and Fe; e.g., Fig. 4). Among feldspathic lunar meteorites it is also at the extreme end of the range for two other geochemical parameters that are characteristic of mare material: (1) low value of *Mg′* (whole-rock mole percent Mg/[Mg + Fe]) and (2) low La/Yb ratio (point V of Figs. 9 and 10). Overall, the composition of Yamato 791197 is consistent with a mixture of 89% feldspathic material (e.g., other feldspathic lunar meteorites) and 11% low-Ti mare basalt (Korotev et al., 1996).

Yamato 82192, 82193, and 86032 (hereafter Yamato 82/86) are paired (Eugster et al., 1989). Concentrations of Sc, Ti, Cr, Mn, and Fe are more variable among subsamples of Yamato 82192 and 82193 (Yamato 82/83) than of the larger Yamato 86032 (and any other feldspathic lunar meteorite) and average concentrations of these elements are greater in Yamato 82/83 than in Yamato 86032 (Fig. 4). Also, Yamato 82/83 has a lower *Mg′* than Yamato 86032 (Fig. 9b). These differences are consistent with a greater, but variable, proportion of a clastic component of mare volcanic material in Yamato 82/83 than Yamato 86032. The average composition of Yamato 82/83 corresponds to that of a mixture of 93% Yamato 86032 and 7% low-Ti mare basalt (Korotev et al., 1996). Feldspathic regoliths with low but varying proportions of mare materials that lead to compositional differences exceeding that between Yamato 82/83 and Yamato 86032 occur within a few centimeters of each other in Apollo 16 regolith drive tube 64001/2 (Korotev et al., 1984), thus the variation in Yamato 82/86 is not unusual. Yamato 82/86 is distinct from other feldspathic lunar meteorites in having the greatest concentrations of Na, Sr, and Eu (Figs. 3a and 4b), indicating that the albite content of the plagioclase is somewhat greater, on average, in this meteorite than in other feldspathic lunar meteorites. Many samples from North Ray Crater at Apollo 16 are similar to Yamato 82/86 in this regard (Fig. 4b; also James et al., 1989).

Yamato 82/86 and Dhofar 081 are both fragmental breccias and both have concentrations of incompatible elements at the low end of the range of feldspathic lunar meteorites (Figs. 4 and 11). Relative concentrations of REEs are distinctly different in the two meteorites, however (Fig. 11), suggesting that they do not derive from the same regolith. QUE 93069 and Dhofar 025 have the greatest concentrations of incompatible elements (Fig. 4) and nearly identical REE patterns (Fig. 11), but differ in other important compositional respects (e.g., *Mg′*; Fig. 9) and

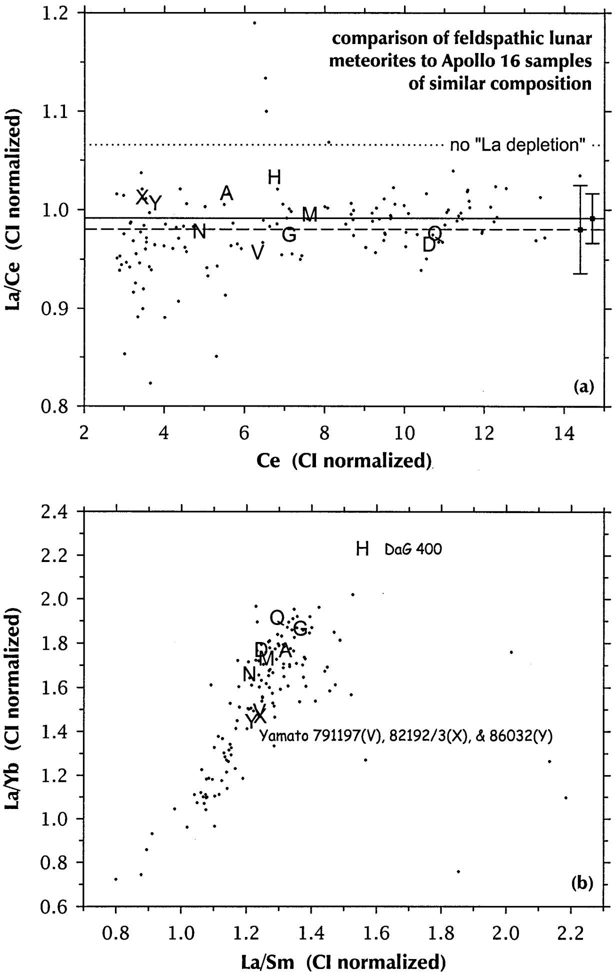

Fig. 10. (a) Comparison of La/Ce ratios in feldspathic lunar meteorites to Apollo 16 samples of similar composition. The mean of the lunar meteorite data (letter symbols; key in Table 1) is indicated by the solid line and the mean of the Apollo 16 data (small points) is indicated by the dashed line. The error bars represent the sample standard deviations of the respective data sets. The figure shows that the meteorites, on average, do not have La/Ce ratios that are anomalous compared to Apollo samples, although DaG 400 (H) is marginally anomalous. The dotted line represents, for the typical feldspathic lunar meteorite, the La/Ce ratio corresponding to no La depletion (Tanimizu and Tanaka, 2002), that is, the line represents the La/Ce ratio resulting from a La concentration lying on the extrapolation from Sm through Ce on a plot such as Figure 11. (b) Comparison of the variation in ratios of light (La) to heavy (Yb) REEs and light (La) to middle (Sm) REEs between feldspathic lunar meteorites and Apollo 16 samples of similar composition. DaG 400 is anomalous and probably contains an excess of light REE from terrestrial alteration. Yamato 791197 (V) and Yamato 82/86 (X/Y) are distinct in being relatively enriched in heavy REE. For both plots (1) all sample data are from this laboratory (meteorites: this work; Korotev et al., 1983, 1996; Jolliff et al., 1991a, Lindstrom et al., 1991a; Apollo 16: this work and Jolliff and Haskin, 1995) and (2) CI data used for normalization are those described in Figure 11.

cosmic-ray exposure parameters (Nishiizumi et al., 1996; Nishiizumi and Caffee, 2001). Among feldspathic lunar meteorites that contain a negligible proportion of mare volcanic material, Yamato 82/86 has the lowest La/Yb ratio whereas DaG 400 is distinct in having the greatest La/Yb ratio (Fig. 10). Among Apollo samples, such a difference would reflect differences in mafic mineralogy. As noted in section 4.3.3, however, the high La/Yb ratio of DaG 400 may be an artifact of terrestrial weathering.

Considering that they are polymict rocks with a narrow range of Al_2O_3 concentrations, feldspathic lunar meteorites have the intriguing property (section 4.5) that *Mg′* varies considerably, from 60 to 73. This range is about the same as that observed among regolith samples (surface and trench) from Apollo 16 (61–72), so differences in *Mg′* of, for example, 5 units between two meteorites is not a strong argument that different meteorites derive from different locations. The *Mg′* for nearly all Apollo 16 soils, however, falls within a narrow range of 64 to 68. Only a few immature regoliths, those dominated by a single lithology and all in the ejecta of North Ray Crater, fall outside that range (Korotev, 1996, 1997). Among feldspathic lunar meteorites, MAC 88104/5 (*Mg′* = 63), Dhofar 026 (63), and Dhofar 081 (~60) are the most ferroan (lowest *Mg′*). ALHA 81005 is the most magnesian (*Mg′* = 73), followed closely by Dhofar 025 (*Mg′* = 71; Fig. 9b). There are no compositional data available yet for Dhofar 489, but it may be even more magnesian on the basis of the petrographic description (Takeda et al., 2003).

For those elements not affected by terrestrial alteration, DaG 262 is nearly indistinguishable in composition from MAC 88104/5, except that concentrations of MgO and siderophile elements (Ni, Co, Ir) are greater in DaG 262. Cosmic-ray exposure data for DaG 262 are ambiguous. Although not strongly supporting the hypothesis, the data do not entirely exclude the possibility that it was launched from the same source crater as MAC 88104/5 (Nishiizumi et al., 1996, 1998). As noted above, however, DaG 262 and MAC 81005 are the most ‘average’ of the feldspathic lunar meteorites, so it may be no special coincidence that they are similar in composition.

Compositionally, NWA 482 is similar to MAC 88104/5 in being reasonably equivalent to a 60:40 mixture of MAC 88104/5 and an anorthosite with 2 to 3% FeO such as sample 60135 of Warren et al. (1983a). This compositional similarity is likely fortuitous in that the ^{10}Be exposure age for NWA 482 of 0.9 ± 0.2 Ma (Nishiizumi and Caffee, 2001) is significantly greater than the 0.26- to 0.29-Ma ejection age of MAC 88104/5 (Nishiizumi et al., 1996). Similarly, the composition of Dhofar 081 corresponds closely to that of a 50:50 mixture of MAC88104/5 and a ferroan anorthosite with 2 to 3% FeO. Again, the preliminary estimate of the Moon to Earth transit time (“short,” Nishiizumi and Caffee, 2001) for Dhofar 081 is less than that of MAC 81004/5.

4.3.2. Siderophile Elements

Concentrations of Ni, Ir, and Au in the brecciated lunar meteorites are comparable to those of Apollo soils. The two meteorites with the highest concentrations of siderophile elements, QUE 93069 and Dar al Gani 262, are among those with the greatest surface exposure, as measured by abundances of trapped solar-wind noble gases (Fig. 8). Variations in concentrations of Ni, Ir, and Au in feldspathic lunar meteorites are consistent with variable proportions of chondritic material (Fig.

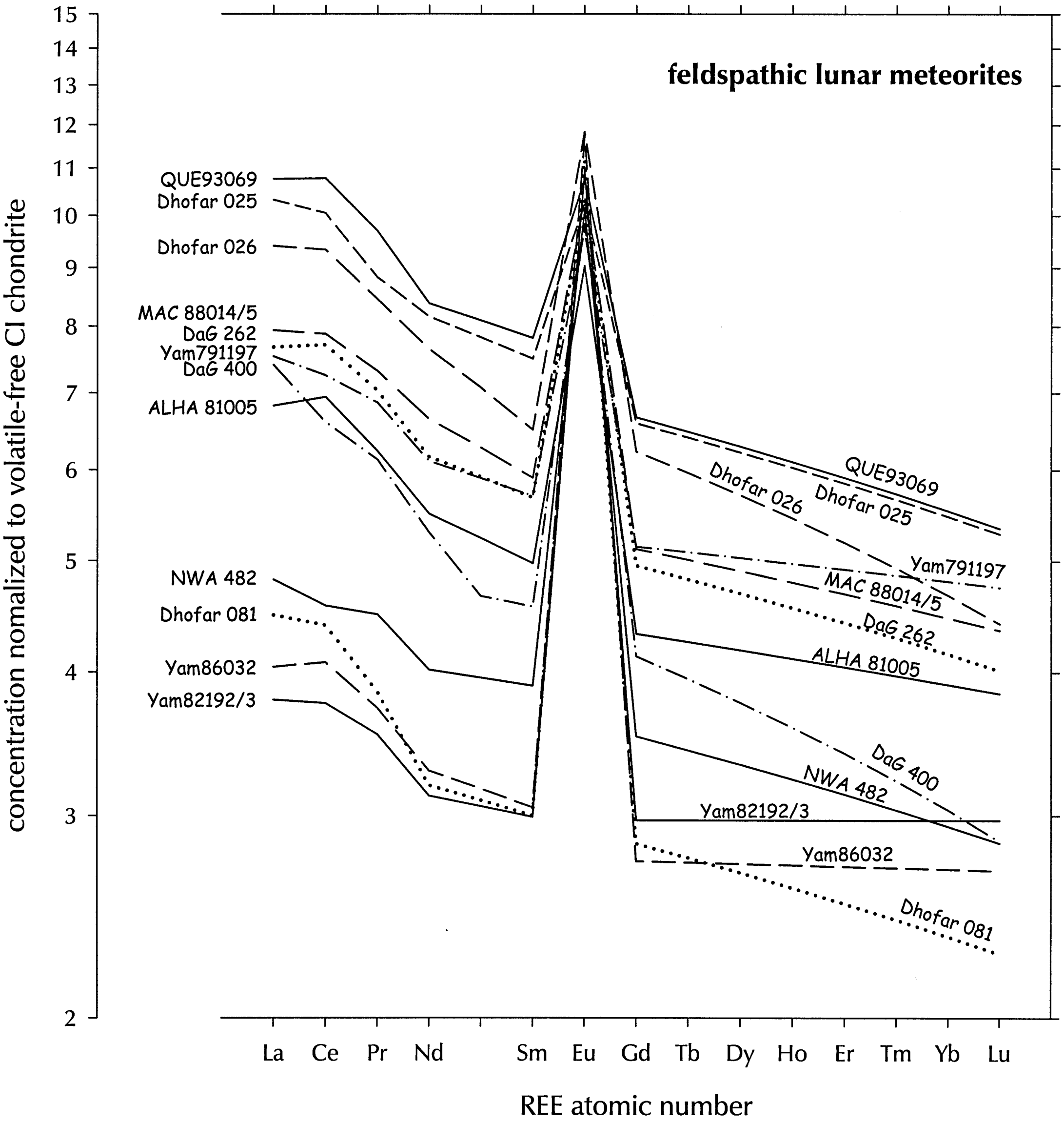

Fig. 11. Concentrations of rare earth element in feldspathic lunar meteorites normalized to volatile-free CI chondrites. In contrast to Figure 10, this figure is based on all available data (references of Table 1). For clarity, the plot is somewhat stylized in that heavy REE (Gd-Lu) line segments are derived from linear regressions. All Pr values are estimated and normalized on the basis of data from the Mainz lab (Palme et al., 1991; Spettel et al., 1995; Bischoff et al., 1998). REE concentrations are normalized by *Ck*, where the values *C* are the "Mean C1 Chondr." values from Table 1 of Anders and Grevesse (1989) and $k = 1.36$, a value that corrects to a volatile-free basis and yields absolute concentrations similar to those of ordinary chondrites (e.g., Nakamura, 1974; Wasson and Kallemeyn, 1988). This figure and Figure 10 show that low La/Ce ratios, with respect to the Ce-Sm slope, are characteristic of feldspathic, low-REE samples as well as REE-rich samples (Tanimizu and Tanaka, 2002).

2). The lowest mean proportion of meteoritic material, 0.7% (volatile-free CI chondrite equivalent; Fig. 11), is in Yamato 82/86, a fragmental breccia. The greatest proportion, 1.9%, is in QUE 93069, a gas-rich regolith breccia. These observations suggest that most of the siderophile elements in lunar meteorites derive from micrometeorites associated with regolith gardening and maturation (Morris, 1980) prior to lithification, not from the impactor that blasted them off the Moon.

In addition to having the greatest concentrations of siderophile elements among lunar meteorites, QUE 93069 also has the greatest concentrations of incompatible elements (Fig. 11). Among Apollo 16 regolith samples there is a correlation between incompatible elements and siderophile elements because (1) anorthositic rocks have low concentrations and the mafic melt breccias have high concentrations of both suites of elements and (2) the soils vary in their proportions of mafic to anorthositic lithologies (Korotev, 1997). However, mafic, KREEP-bearing melt breccias like those of the Apollo sites are not the cause of the high siderophile and incompatible element concentrations in QUE 93069 and Dar al Gani 262 because the siderophile-to-incompatible element ratio in the KREEP-bearing melt breccias is much too low to account for the variations among the lunar meteorites. If there is a correlation between siderophile elements and incompatible elements among those lunar meteorites that are regolith and fragmental breccias, it is likely to arise from the following process. Plutonic rocks of the feldspathic highlands contain very low concentrations of siderophile and incompatible elements (Warren and Wasson, 1978). With time, a surface consisting originally of feldspathic, plutonic rocks accumulates (1) extralunar siderophile elements from micrometeorites and (2) incompatible elements from the redistribution of Sm- and Th-rich material by large impacts into the Procellarum KREEP Terrane. Thus, the longer a feldspathic regolith matures *in-situ* (McKay et al., 1974), the higher the concentrations of accumulated siderophile and incompatible elements.

4.3.3. *Rare Earth Elements and La/Ce Anomaly*

In a study of shergottites DaG 476 and 489, Crozaz and Wadhwa (2001) questioned whether hot-desert meteorites and their minerals retain the compositional and isotopic signatures of their parent bodies. In particular, the study addressed the behavior of REEs. Terrestrial weathering is the cause of Ce anomalies in minerals of both hot- and cold-desert meteorites (Crozaz and Wadhwa, 2001; Floss and Crozaz, 2001). Our data provide some information about whole-rock mass balance for REEs in lunar meteorites.

Among the ten feldspathic lunar meteorites that we have analyzed, the range of CI-normalized La/Ce ratios (among the 10 mass-weighted means) is 0.957 to 1.033 with a mean of 0.991 (Fig. 10a). There is no indication that La/Ce for the four hot-desert meteorites ($\bar{x} = 0.989$, $s = 0.031$) is significantly different from that for the six Antarctic meteorites ($\bar{x} = 0.994$, $s = 0.021$). Also, none of the meteorites, except perhaps for DaG 400, is anomalous compared to the Apollo 16 comparison suite (Fig. 10a). Thus our data offer no evidence of a significant bulk fractionation of Ce from La during terrestrial weathering of feldspathic lunar meteorites. DaG 400, however, is enriched overall in light REE (Fig. 11), with La being the most anomalous compared to Apollo samples (Fig. 10b). This enrichment may be a terrestrial alteration effect, although we do not know the mechanism (phosphate deposition?).

In a recent paper Tanimizu and Tanaka (2002) argue that lunar KREEP-rich and magnesian-suite rocks are depleted in La with respect to Ce and Nd, but that ferroan anorthosite is not. The low-La/Ce effect observed by Tanimizu and Tanaka (2002) is also evident in the feldspathic lunar meteorites and the Apollo 16 comparison suite (Figs. 10a and 11), all of which are feldspathic and KREEP poor. The relative magnitude of the apparent depletion does not increase with increasing REE concentration (Fig. 10a), so the anomaly in the feldspathic samples can not be the result of admixture of KREEP-rich rocks to ferroan anorthosite. Our own observation, which differs slightly from the conclusion of Tanimizu and Tanaka (2002), is that most nonmare samples, except perhaps highly feldspathic ferroan anorthosite, appear to have low La (or high Ce) relative to the overall slope of the light REE (e.g., Fig. 11).

4.4. The Composition of the Feldspathic Upper Crust

Numerous studies of the first lunar meteorite, ALHA 81005, concluded that because it was a feldspathic breccia having concentrations of incompatible elements that were low compared to the Apollo 16 regolith (e.g., Fig. 6) and only minor amounts of mare volcanic material, it could not have originated from a location near the Apollo sites but must have derived from a place distant from nearside concentrations of KREEP and mare basalt, perhaps the farside (Kallemeyn and Warren, 1983; Korotev et al., 1983; Palme et al., 1983; Pieters et al., 1983; Ryder and Ostertag, 1983; Warren et al., 1983b). The farside connection was established in part by the low FeO, MgO, and Th concentrations inferred for the farside from the partial coverage obtained by the Apollo orbiting gamma-ray experiments (Bielefeld et al., 1976; Metzger et al., 1977; Davis, 1980). The similarity between the composition of ALHA 81005 and estimates of the average surface composition of the feldspathic highlands was also noted (Palme et al., 1983; Korotev et al., 1983). Similar conclusions and comparisons have subsequently been made numerous times about the other feldspathic lunar meteorites (e.g., Warren and Kallemeyn, 1986; Jolliff et al., 1991a; Palme et al., 1991; Korotev et al., 1996). At the point when five feldspathic lunar meteorites were known and it was clear that they were ejected from several craters at apparently random locations in the highlands, Palme et al. (1991) proposed that the average composition of the meteorites "may provide a good average for the chemical composition of the lunar highlands." The global geochemical data provided by the Clementine (Lucey et al., 1995, 2000) and Lunar Prospector (LP) missions (Lawrence et al., 1998, 2000; Elphic et al., 2000) allow a test of that proposition. As noted in the "Introduction," the lunar meteorites are especially useful for this purpose because most are regolith breccias. As a consequence, their compositions are likely to represent well the regional surface composition of the places from which they originate (Warren, 1994; Korotev et al., 1996; Korotev, 2000). The impact-melt breccias are also useful for this purpose because they represent significant volume of material, but perhaps of deeper origin than the regolith breccias (section 4.2.3).

The two most useful chemical elements for providing first-order compositional (and by inference, mineralogical) information about lunar samples are iron and aluminum (Fig. 1). Fortunately, iron is one of the elements for which concentrations have been measured or estimated from data acquired by orbiting spacecraft. In Figure 12 we compare the distribution of FeO concentrations on the lunar surface obtained from the lunar meteorites (Fig. 12a) with those obtained globally from orbit (Figs. 12b–12d). Given the differences among the distributions obtained by various techniques for deriving FeO concentrations from UV-VIS reflectance or gamma-ray spectra obtained from orbit, Figure 12 does not negate the proposition that the brecciated lunar meteorites are random samples of lunar surface regolith. This particular test only establishes the representativeness of the meteorites in terms of the FeO dimension of the regolith mixing triangle of Figure 6. A similar comparison for Th in Figure 13 also shows a reasonable match between the lunar meteorites and the most recent published derivation of Th concentrations from the LP-GRS (gamma-ray spectrometer). Samarium concentrations derived indirectly from the LP-NS (neutron spectrometer; Elphic et al., 2000) could also be used in principle, but they are unrealistic in that many negative concentrations occur. The selection and testing of procedures, algorithms, and assumptions used for deriving

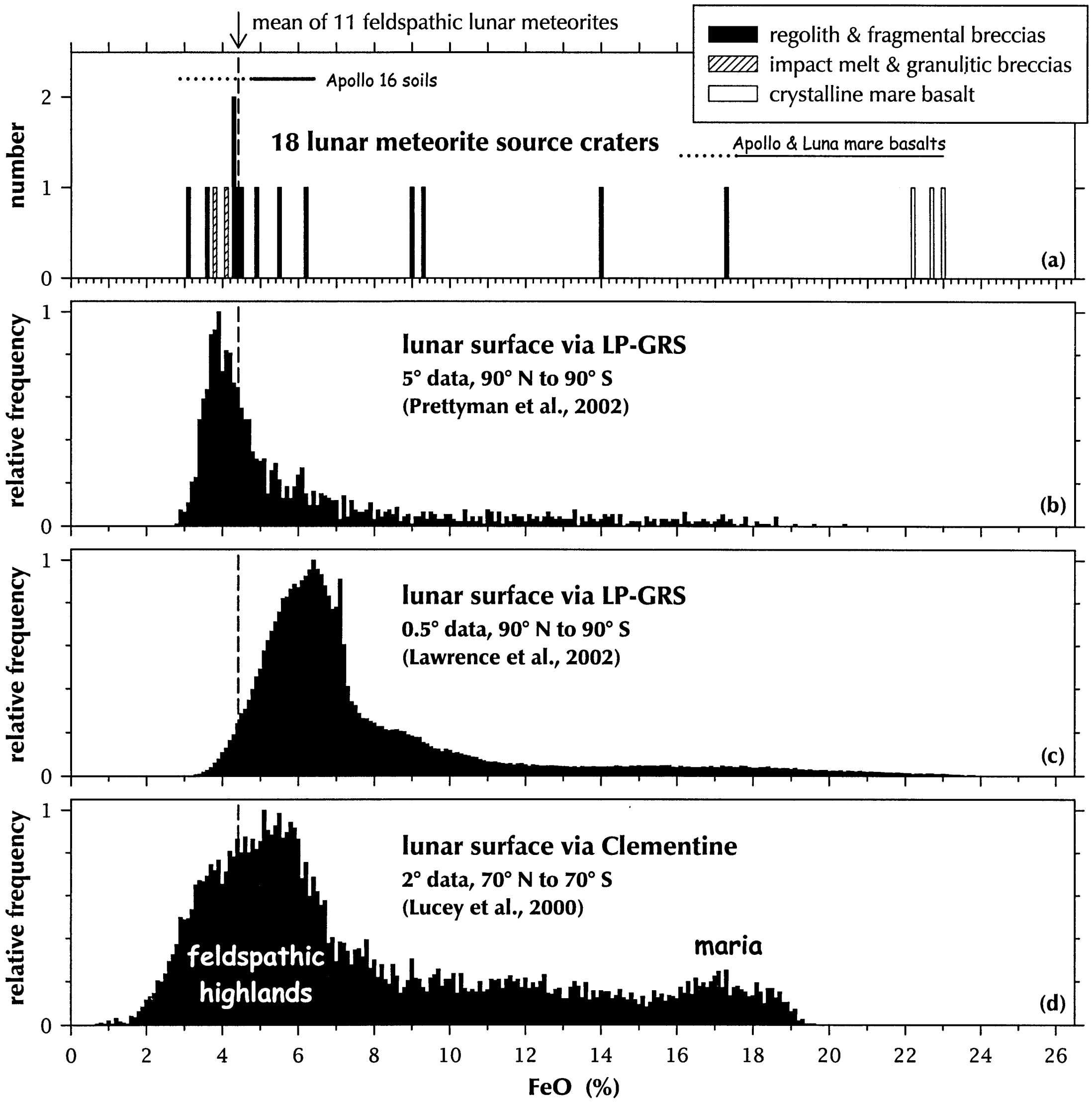

Fig. 12. Comparison of estimates and measurements of the distribution of FeO on the lunar surface. (a) Distribution of FeO concentrations (total iron as FeO) in source regions of lunar meteorites. For this plot we assume the lower limit estimated in section 4.2.2 for the number of possible source craters represented by the lunar meteorites (18), except that, pending cosmic-ray exposure data for Yamato 983885, we assume that it is not launch paired with Calcalong Creek (18 + 1 = 19) and there are no FeO data available yet for Sayh al Uhaymir 169 (19 − 1 = 18). For those meteorites that we assume to be launch paired and for Yamato 82/86, the bar is plotted at a concentration corresponding the mass-weighted mean based on the masses of the individual stones. The range of compositions of mature surface and trench soils from Apollo 16 is shown by the solid horizontal line at low FeO; the dotted line represents the range of immature and submature soils from North Ray Crater (Korotev, 1996, 1997). The solid horizontal line at high FeO represents the range of most mare basalts from the Apollo and Luna missions; the dotted portion corresponds to the aluminous basalts of Apollo 14 (Dickinson et al., 1985; Neal et al., 1988). (b–d) Concentrations derived from data acquired from orbit. The LP (Lunar Prospector) GRS (gamma-ray spectrometer) results are those of Prettyman et al. (2002) (June 2002 data) and Lawrence et al. (2002) (January 2002 data). For the Clementine results of Lucey et al. (2000), 94% of the lunar surface lies between 70°S and 70°N. The peak at low-FeO concentration corresponds mainly to farside, northern highlands.

element concentrations from orbital data acquired by Clementine and Lunar Prospector has been an iterative process and efforts continue (e.g., Lawrence et al., 2003). The differences among the various attempts for FeO and Th attest to the difficulty of the process. We conclude, nevertheless, that the comparisons of Figures 12 and 13 show the brecciated lunar meteorites to be reasonably representative of the lunar surface.

If we turn the argument around and start by assuming that the lunar meteorites are, in fact, random samples from numerous locations on the lunar surface, then the meteorites can provide some guidance in the calibration of orbital data (Gillis et al., 2000; Haskin et al., 2000; Fig. 5). With the same assumption the meteorites also provide a good, and perhaps the best, estimate of the average composition of the surface of the feldspathic highlands in regions largely uncontaminated with high-Th material originating from the Procellarum KREEP

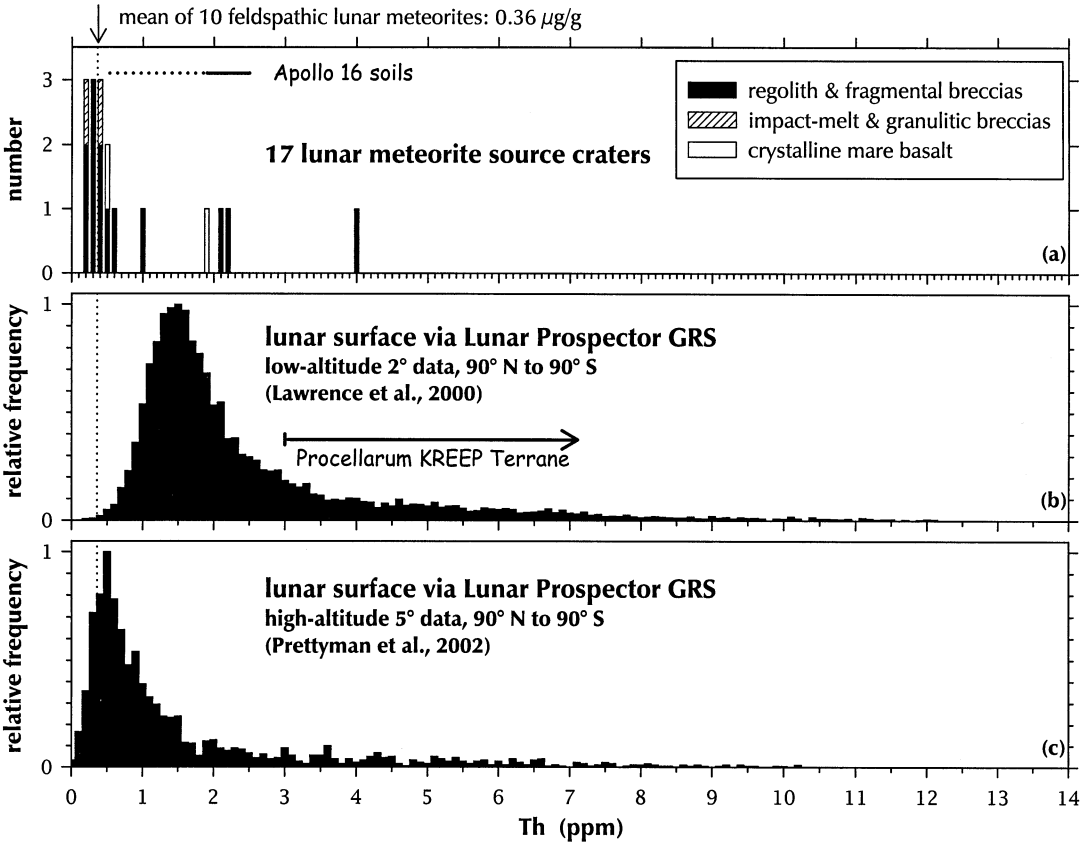

Fig. 13. Similar to Figure 12, but for Th. All feldspathic lunar meteorites have ≤ 0.6 ppm Th. (a) There is one fewer meteorite plotted than in Figure 12a because there are no Th data available yet for mare basalt Dhofar 287. Sayh al Uhaymir 169, an impact-melt breccia, lies off the plot at 33 ppm (Gnos et al., 2003). (b) Th concentrations derived from the LP-GRS by Lawrence et al. (2000) (with June 2001 update of data) using a simple peak-over-background technique are systematically high, at least at low Th concentrations, compared the lunar meteorites. The mode (1.4 ppm) exceeds the mean of the feldspathic lunar meteorites (0.36 ppm) by a factor of 3.6. (c) The distribution of Th concentrations derived by Prettyman et al. (2002) (data of June 2002), using a library least-squares technique, more closely match the distribution of the brecciated lunar meteorites and yields a highlands mode (0.5 ppm) slightly greater than the mean of the feldspathic lunar meteorites.

Terrane and mare volcanic material. Following the lead of Palme et al. (1991) and our own previous effort (Korotev, 2000), we present such an estimate in Table 5. The estimate is based on the mean composition of the eight best characterized of the feldspathic lunar meteorites: ALHA 81005, MAC 88104/5, QUE 93069, Yamato 86032, DaG 262, DaG 400, Dhofar 025, and NWA 482 (points for these eight meteorites are circled in Fig. 1b). For each element, we first calculated average concentrations for each of the meteorites (simple mean of available data) and then we averaged the means for the eight meteorites. We do not include Yamato 791197 or the Yamato 82/83 portion of Yamato 82/86 because these stones contain a non-negligible proportion of mare volcanic material and consequently are at the high-FeO, low-Al_2O_3 end of the compositional range (section 4.3.1; Fig. 1b). For the four hot-desert meteorites, we use estimates of the pre-fall concentrations of K, Ca, Rb, Sr, Ba, and Au based on interelement correlations among cold-desert meteorites such as those of Figures 2b and 3 instead of the observed concentrations. For DaG 400, we also estimate pre-fall concentrations of La, Ce, and Nd based on the mean La/Sm ratios, etc., of the other meteorites (section 4.3.3). Our new estimate yields a more feldspathic (28.2% Al_2O_3) mean composition for the of the surface of the feldspathic highlands than that of Palme et al. (1991) (26.1% Al_2O_3) mainly because Palme et al. (1991) included Yamato 791197 and both the 82192/3 and 86032 stones of Yamato 82/86 as separate items in their average. For all the precisely determined lithophile elements, however, our new estimates are within 3% of our previous estimates (Korotev, 2000), which were based on five meteorites, only one of which was from a hot desert.

The brecciated lunar meteorites, and the upper few meters of the Moon that they represent, all contain extralunar meteoritic material from impacts of countless micrometeorites and some crater-forming meteorites. On average, the feldspathic lunar meteorites contain ~1% extralunar material (volatile-free CI chondrite equivalent; Fig. 2). This material is concentrated near the surface, so the feldspathic upper crust (FUpCr) likely contains a lower proportion, on average. To obtain an estimate of the composition of the upper few kilometers of lunar crust uncontaminated by extralunar material (FUpCr of Table 5), we calculated concentrations of each element (C_{FUpCr}) from the mass-balance equation $C_{\mathrm{Surface}} = f C_{\mathrm{CI}} + (1 - f) C_{\mathrm{FUpCr}}$, where

Table 5. Estimates of the concentrations some mostly lithophile elements in the upper few meters (Surface) and upper few kilometers (FUpCr) of typical feldspathic crust based on feldspathic lunar meteorites.

	Unit	Surface	±	FUpCr		Unit	Surface	±	FUpCr
SiO_2	%	44.7	0.3	44.9	Zr	ppm	35	11	35
TiO_2	%	0.22	0.04	0.22	Ba	ppm	33	10	33
Al_2O_3	%	28.2	1.0	28.5	La	ppm	2.3	0.6	2.4
Cr_2O_3	%	0.096	0.014	0.092	Ce	ppm	6.0	1.6	6.0
FeO	%	4.4	0.5	4.0	Pr	ppm	0.8	0.2	0.8
MnO	%	0.063	0.004	0.060	Nd	ppm	3.6	0.9	3.7
MgO	%	5.4	1.4	5.3	Sm	ppm	1.1	0.3	1.1
CaO	%	16.3	0.9	16.4	Eu	ppm	0.78	0.05	0.79
Na_2O	%	0.35	0.03	0.34	Gd	ppm	1.3	0.3	1.3
K_2O	%	0.027	0.008	0.026	Tb	ppm	0.23	0.05	0.23
P_2O_5	%	0.027	0.009	0.023	Dy	ppm	1.5	0.4	1.5
Σ	%	99.8		99.9	Ho	ppm	0.33	0.08	0.33
Mg′	%	69	3	70	Er	ppm	0.9	0.2	0.9
K	ppm	220	60	210	Tm	ppm	0.14	0.03	0.14
Sc	ppm	8.0	1.0	8.0	Yb	ppm	0.89	0.2	0.90
Cr	ppm	660	90	630	Lu	ppm	0.13	0.03	0.13
Mn	ppm	490	40	460	Hf	ppm	0.8	0.2	0.8
Co	ppm	17	3	10	Ta	ppm	0.11	0.02	0.11
Ni	ppm	185	45	~16	Ir	ppb	7.5	2.8	=0
Rb	ppm	0.7	0.3	0.7	Au	ppb	2.8	1.0	~0.6
Sr	ppm	150	12	151	Th	ppm	0.37	0.11	0.38
Y	ppm	9	2	9	U	ppm	0.16	0.10	0.16

"Surface" is essentially the mean composition of lunar meteorites ALHA 81005, MAC 88105, QUE 93069, Yamato 86032, DaG 262, DaG 400, Dhofar 025, and NWA 482 based all literature data (Table 1), except that estimated concentration values were used for data suspected to be compromised by terrestrial contamination (K, Ca, Rb, Sr, Ba, and Au; see text). Values for Y, Pr, Gd, Dy, Ho, Er, and Tm were estimated from the other REE. The uncertainty (±) is the 95% confidence limit on the mean values. "FUpCr" (feldspathic upper crust) is an estimate of the composition of the upper few kilometers of the crust and differs from the surface composition only in the absence of a component of CI chondrite (1.58%; values of Anders and Grevesse, 1989, or 1.16% on a volatile-free basis, e.g., Fig. 11).

$C_{Surface}$ are the surface concentrations of Table 5, C_{CI} are the concentrations in volatile-free CI chondrites (Fig. 11), and f is the mass fraction of meteoritic material. The value f was assumed to be 1.16%, the value that yields $C_{FUpCr} = 0$ for Ir. Although this correction has negligible effect on most lithophile elements, it has a significant effect on iron in that 10% of the iron in the surface material of the feldspathic highlands derives from extralunar material. A large fraction of this extralunar iron is in metallic form (e.g., Morris, 1980; Korotev, 1997).

With 28.5 ± 1.0% Al_2O_3, our new estimate for the average composition of the feldspathic upper crust corresponds to 79 mass%, or ~83 vol.%, plagioclase (Fig. 14). This estimate is strictly applicable only to the upper few kilometers of the Moon, roughly the thickness of combined ejecta deposits from the large basins (Short and Foreman, 1972). Is it also applicable to upper few tens of kilometers? There is evidence that material that is more feldspathic, > 90% plagioclase, occurs at depth and might be extensive in distribution (Blewett et al., 2002; Peterson et al., 2002; Hawke et al., 2003). Even among our limited samples, however, highland regoliths vary considerably in plagioclase abundance. At one extreme, with ~31% Al_2O_3, the "primordial upper crust" (Stöffler et al., 1985) or "prebasin" (essentially, pre-Imbrium; Korotev, 1997) component of the Apollo 16 regolith is more feldspathic than all but the most extreme of the lunar meteorites (Figs. 1b and 9a). In contrast, with 23% Al_2O_3, the regolith of the Luna 20 site is less feldspathic than any of the feldspathic lunar meteorites (Fig. 9a). Unlike the Apollo 16 regolith, the Luna 20 regolith is not a mixture of feldspathic materials and mafic, KREEP-rich materials; it contains little mare material and little or no KREEP (Prinz et al., 1973; Taylor et al., 1973). Instead, it is dominated by feldspathic materials that are somewhat more mafic, on average, than those of Apollo 16 (Fig. 15). The regoliths of the Apollo 16 and Luna 20 sites are important to

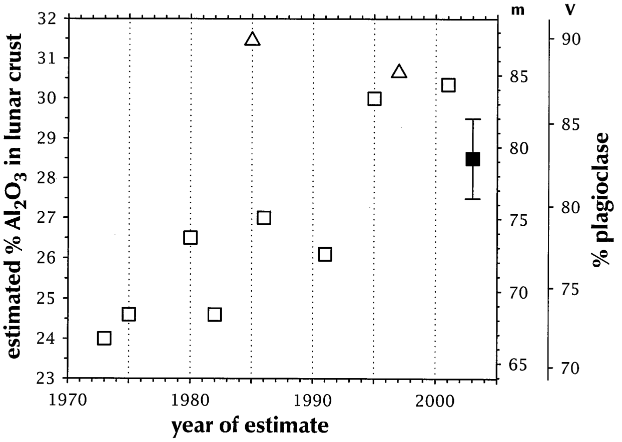

Fig. 14. Recent estimates of the concentration of Al_2O_3 (i.e., plagioclase) in the lunar crust have tended to be greater than early estimates. Explicitly or by inference from the data and procedures by which the estimate was obtained, the estimates mainly apply to the upper crust. Data from Turkevich (1973, p. 1164), Taylor (1975, p. 252), Korotev et al. (1980, p. 402), Taylor (1982, p. 230), Stöffler et al. (1985, p. 498), Spudis and Davis (1986, p. E87), Palme et al. (1991, p. 3120), Lucey et al. (1995, p. 1153), Korotev (1997, p. 466), Wieczorek and Zuber (2001) (mean of stated range = 28.5–32.2%), and this work (2003; filled square). The two triangles represent estimates based only on Apollo 16 samples. The axes on the right side of the plot indicate the normative (mass) proportion of plagioclase and the approximate volume percentage.

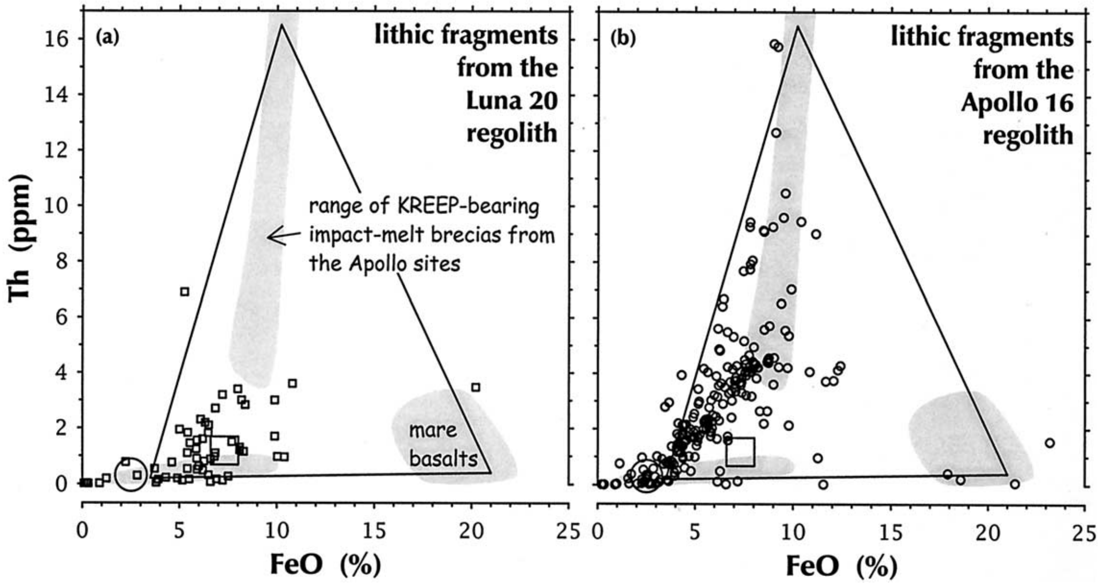

Fig. 15. (a) The small squares each represent lithic fragments from the Luna 20 regolith. All available data are plotted and the average fragment mass is small (~1 mg). The large square represents the average composition of the Luna 20 fines (soil); the large circle represents the prebasin components of the Apollo 16 regolith (Fig. 1b). Compare with Figure 6a. (b) Like (a), but for "large" (>20 mg) fragments from regoliths of the Cayley Plains of Apollo 16. The components of the Apollo 16 regolith vary widely in composition. The figure suggests that the Luna 20 regolith is rich in FeO compared to the pre-Imbrium material of the central Highlands (Apollo 16) because it is composed of moderately mafic highlands lithologies, not because it is a mixture of feldspathic material and mare basalt (like the regoliths of the Apollo 15 and 17 sites) or because it contains FeO- and Th-rich (KREEP-bearing) impact-melt breccias (like the Apollo 16 regolith). Luna 20 data are from Laul and Schmitt (1973a), Jérome and Philipott (1973) (Th values estimated from Sm), Smith et al. (1983), Korotev and Haskin (1988), and Swindle et al. (1991). Apollo 16 data are from Korotev et al. (1997).

interpretation of the feldspathic lunar meteorites because the non-KREEP components of the Apollo 16 regolith contain a substantial proportion of ejecta from the Nectaris and perhaps the Serenitatis basins (Spudis, 1984; Haskin, 2001) whereas the Luna 20 regolith developed on the Crisium ejecta deposit (Spudis and Pieters, 1991). Thus the compositional variation among highland regoliths likely reflects, to some extent, variations with depth of the early lunar crust.

4.5. Mg' of the Lunar Crust and Magnesian Granulitic Breccias

The Luna 20 regolith (symbol "%" of Fig. 9a), the prebasin (i.e., feldspathic) components of the Apollo 16 regolith (symbol "$"), and the feldspathic upper crust, as estimated from the feldspathic lunar meteorites (symbol "#" and Table 5) each share an important geochemical characteristic. Despite a range of Al_2O_3 concentrations, Mg' for each is ~70, which is at the high end of the range for ferroan anorthosite (40–70, but typically 50–65, e.g., samples of Table 12 of Papike et al., 1998). One self-evident interpretation of this observation is that a significant portion of the Fe and Mg in the lunar crust is not derived from ferroan anorthosite but from rocks of the magnesian ("Mg-rich") suite of lunar plutonic rocks, e.g., the norites and troctolites of the Apollo collection (see summaries of Taylor et al., 1991, and Papike et al., 1998). We argue here, however, that a link between the high Mg' of the feldspathic lunar crust and magnesian-suite plutonic rocks of the Apollo collection cannot be established.

Among feldspathic lunar meteorites Mg' is variable and it correlates with the abundance of normative olivine (Fig. 9b). High-Mg' meteorites such as ALHA 81005, Dhofar 025, and Dhofar 489 all contain lithologies having olivines of $Fo_{>80}$ composition (Ryder and Ostertag, 1983; Treiman and Drake, 1983; Warren et al., 1983b; Goodrich et al., 1984; Takeda et al., 2003). High Mg' in feldspathic lunar meteorites occurs when a significant fraction of the mafic minerals are forsteritic olivines.

Feldspathic lunar meteorites with high Mg' contain clastic materials from both ferroan ($Mg' < 70$) and magnesian ($Mg' > 70$) rocks, and most of the magnesian clasts are feldspathic granulitic breccias, troctolitic anorthosites and anorthositic troctolites, or magnesian anorthosites (Treiman and Drake, 1983; Kurat and Brandstätter, 1983; Warren et al., 1983b; Goodrich et al., 1984; Cahill et al., 2001; Takeda et al., 2003). In other words, nearly all high-Mg' lithologies in feldspathic lunar meteorites are feldspathic. Clasts of mafic, high-Mg' lithologies, such as the norites, troctolites, and dunites of Apollo 15 and 17, are rare to absent. Similarly, high-Mg' lithologies are common in the Luna 20 regolith (Brett et al., 1973; Cameron et al., 1973; Kridelbaugh and Weill, 1973; Meyer, 1973; Prinz et al., 1973; Reid et al., 1973; Roedder and Weiblen, 1973; Taylor et al., 1973; Cohen et al., 2001) and the Apollo 16 regolith (e.g., Lindstrom and Lindstrom, 1986; James et al., 1989), and these lithologies tend to be feldspathic, not mafic.

The remaining discussion focuses mainly on granulitic breccias because they are widespread and because they are the most

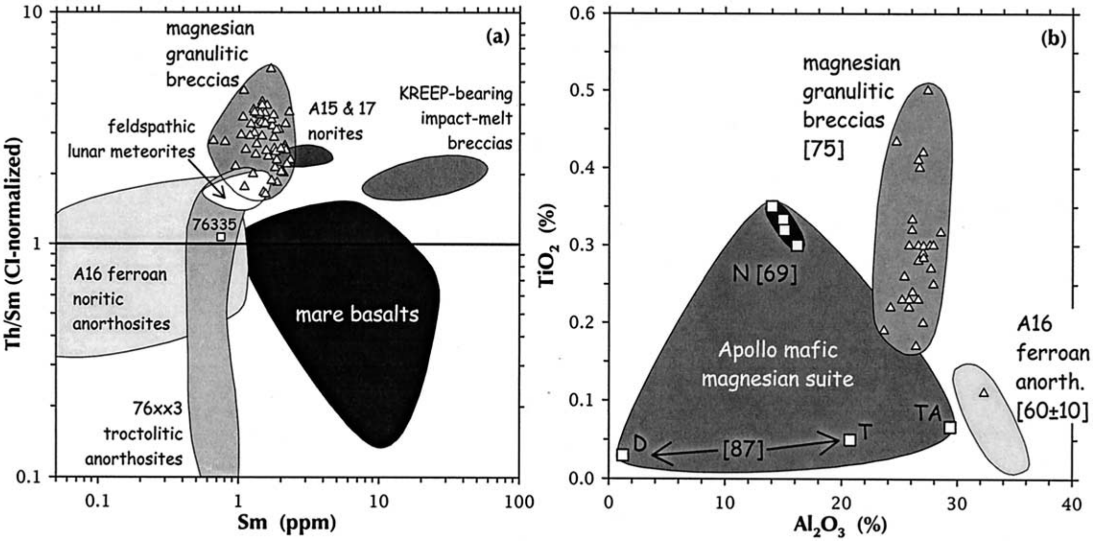

Fig. 16. (a) Magnesian granulitic breccias (triangles) cannot be mixtures of known igneous and plutonic rocks because they have greater Th/Sm ratios, on average, than (1) ferroan-anorthositic-suite rocks such as Apollo 16 ferroan noritic anorthosites, (2) mafic magnesian-suite rocks such as the Apollo 15 and 17 norites and Apollo 17 troctolitic anorthosites, including 76335 (square; there are no Th data for troctolite 76535), (3) KREEP-bearing impact-melt breccias, and (4) mare basalts. (b) Similarly, there is no known lithologic component or mixture thereof that can simultaneously account for the high TiO$_2$ and high *Mg′* (in square brackets) of the magnesian granulitic breccias. The squares represent dunite (D, 72415), troctolite (T, 76535), troctolitic anorthosite (TA, 76335), and norites (N). Granulitic breccia data are from Blanchard et al. (1977), Boynton et al. (1976), Hubbard et al. (1974), Jolliff et al. (1996), Laul and Schmitt (1973b), Laul et al. (1974, 1983b), Lindstrom and Lindstrom (1986), Lindstrom and Salpas (1981, 1983), Lindstrom et al. (1977), Palme et al. (1978), Wänke et al. (1976), Warren et al. (1990), Wasson et al. (1977). Other date are from Jolliff and Haskin (1995) (67513 ferroan-anorthositic suite), Jolliff et al. (1996) (Apollo 17 troctolitic anorthosites), Warren and Wasson (1978) (76335), Ryder and Norman (1979) (and references therein; Apollo 15 and 17 norites, dunite, and troctolite), Korotev (2000) (impact-melt breccias), and numerous literature sources (mare basalts).

important magnesian feldspathic lithology in the lunar highlands. Granulitic breccias were found at most of the Apollo sites (James and Hammarstrom, 1977; Warner et al., 1977; Bickel and Warner, 1978; James, 1980; Stöffler et al., 1985; Lindstrom and Lindstrom, 1986; Cushing et al., 1999). They occur as small individual rocks, fragments in soils, and as lithic clasts in breccias, including lunar meteorites. Isotopic data on granulitic breccias are scarce. ^{40}Ar-^{39}Ar data yield ages mostly in the range 3.9 to 4.1 Ga, perhaps some as old as 4.3 Ga, and the younger ages may have been reset by the events that exhumed the rocks (James, 1980; Papike et al., 1998). Feldspathic granulitic breccias must have been assembled prior to the dispersal of KREEP (Warner et al., 1977; Papike et al., 1998) and they are rare at locations where KREEP is most abundant (e.g., we are unaware of any such samples in the Apollo 12 and 14 collections).

Lindstrom and Lindstrom (1986) made the important observation that *Mg′* varied among granulitic breccias but was nearly dichotomous, with ferroan (low-*Mg′*) and magnesian (high-*Mg′*) varieties. Compositions of ferroan granulitic breccias are unremarkable in that they are consistent with derivation the ferroan anorthositic suite of lunar plutonic rocks. It is the magnesian granulitic breccias that are enigmatic. Although the breccias are feldspathic, *Mg′* averages ~75 (range 72–80), significantly greater than ferroan anorthosite or typical regolith from the highlands (Fig. 9a). If the magnesian granulites, as highlands breccias, contain a component of ferroan-anorthositic suite rock, that component must either be volumetrically negligible or consist of nearly pure plagioclase (i.e., negligible FeO and MgO). Magnesian granulitic breccias clearly derive from some high-*Mg′*, olivine-bearing but plagioclase-rich lithology of the feldspathic crust, one largely uncontaminated with KREEP and one not closely related to ferroan anorthosite.

It is tempting to conclude that magnesian granulitic breccias derive from rocks of the magnesian suite of nonmare plutonic rocks (Warner et al., 1977; James and Hammarstrom, 1977; Bickel and Warner, 1978; James, 1980; Stöffler et al., 1985; Lindstrom and Lindstrom, 1986; Papike et al., 1998; Cushing et al., 1999), but there are compositional impediments to a connection. Although magnesian granulitic breccias are common at the Apollo 17 site, their compositions do not correspond to those magnesian-suite norites, troctolites, troctolitic anorthosites, or any mixture of these that also occur at the site (Fig. 16). Ratios such as Sc/Sm and Ti/Sm in magnesian granulitic breccias are outside the ranges of those in magnesian-suite rocks (Norman and Ryder, 1980; Warren et al., 1981). For example, Ti/Sm ratios of magnesian granulitic breccias (~900) are a factor of 2 greater than those of Apollo 17 norites and troctolitic anorthosites. Curiously, magnesian granulitic breccias from both Apollo 16 and 17 have Th/Sm ratios that are high compared to feldspathic lunar meteorites, magnesian-suite rocks, and KREEP (Fig. 16). Mixing of known types of igneous and plutonic rocks cannot explain this feature. Ratios of Th to Sm as high as 3 to 5 times the chondritic ratio (Fig. 15) are difficult to explain by igneous fractionation caused by the common lunar rock-forming minerals. Magnesian granulitic breccias might derive from magnesian (troctolitic) anorthosites, such as those from Apollo 16 sample 64435 (James et al., 1989), but this connection has not been demonstrated.

It has long been assumed that the magnesian-suite norites and troctolites are rocks of the lunar highlands in that they derive from intrusions into the feldspathic crust and that they occur throughout the feldspathic crust (e.g., James, 1980; Spudis and Davis, 1986; Warren, 1988; Snyder et al., 1995; Papike et al., 1996, 1998). The well-studied magnesian-suite rocks appear to have formed from KREEP-rich parent melts (Warren, 1988; Snyder et al., 1995; Papike et al., 1996), however, and the conditions necessary to produce such rocks may be restricted to the Procellarum KREEP Terrane (Jolliff et al., 2000; Korotev, 2000). There is no actual evidence that intrusive bodies with the necessary characteristics—mafic and KREEP-bearing—actually occur anywhere in the feldspathic highlands, at least not on a broad enough scale to be detected by the orbital spacecraft or Earth-based astronomy.

The magnesian granulitic breccias clearly do not originate from the Procellarum KREEP Terrane. We are left with the following ironies: (1) the magnesian granulitic breccias more likely derive from impacts into high-Mg/Fe regions (intrusions?) of the feldspathic crust than are any of the known mafic magnesian-suite plutonic rocks and (2) although they are magnesian and have mineral compositions consistent with magnesian-suite rocks (Lindstrom and Lindstrom, 1986), the magnesian granulitic breccias are probably unrelated to the mafic magnesian-suite rocks of the Apollo collection. In effect, we must consider that there may be two unrelated magnesian suites, one associated with the Procellarum KREEP Terrane and another associated with some part or parts of the Feldspathic Highlands Terrane. The appeal of a magnesian suite confined to the Procellarum KREEP Terrane is that the concentration of KREEP deep in the crust and perhaps extending into the upper mantle provides a needed source of heat for remelting early-formed cumulates. What is the heat source to produce melts that intrude the thicker crust of the Feldspathic Highlands Terrane? To what level could such melts rise?

In a survey of central peaks of 109 globally distributed impact craters in the highlands, Tompkins and Pieters (1999) identified rock types (or mixtures of rock types) that are consistent with granulitic breccias (gabbroic-noritic-troctolitic anorthosites); more mafic rocks such as most of the magnesian-suite samples of the Apollo collection (gabbronorite, norite, troctolite, dunite) were not common. The diversity of Mg/Fe ratios observed among granulitic breccias is consistent with the lithologies inferred to occur in the central peaks. The range of crater sizes studied by Tompkins and Pieters (1999), 40 to 180 km in diameter, is consistent with the size of craters required to produce granulitic breccias, 30 to 90 km (Cushing et al., 1999). We think it more likely, however, that magnesian granulitic rocks were assembled by one or a small number of very large impacts that penetrated to mid crustal levels or deeper and produced thick ejecta deposits, and that later basin-sized and large-crater events brought these rocks to the surface and distributed them widely. The abundance of granulitic breccias at the Apollo 16 and 17 and Luna 20 sites may implicate the Serenitatis, Crisium, Fecunditatis, and/or Nectaris events, but their presence in the feldspathic lunar meteorites implicates other unknown basins as well, perhaps including South Pole-Aitken.

5. CONCLUSIONS

Regoliths from the Apollo missions all contain high proportions of mare volcanic material or Th-rich material likely originating from the anomalous high-Th region on the nearside of the Moon (Fig. 5). As a consequence, none of the Apollo regoliths has a composition that is truly representative of the most common lunar terrane (Jolliff et al., 2000), the feldspathic highlands. All feldspathic lunar meteorites are breccias, and most are breccias composed of regolith. The average concentrations of FeO (4.4 ± 0.5%) and Th (0.37 ± 0.11 ppm) in the eight best characterized feldspathic lunar meteorites are largely consistent with modes in the distribution of concentrations derived from orbital data over the feldspathic highlands (Lucey et al., 2000; Lawrence et al., 2002, 2003; Prettyman et al., 2002). Means for these two elements based on all eleven meteorites of Table 1 are nearly identical, 4.4 ± 0.6% FeO and 0.36 ± 0.08 ppm Th. Thus, the meteorite mean (Table 5) provides the best currently available estimate of the composition of the surface of the feldspathic crust in regions, such as the farside highlands, that are minimally contaminated with mare volcanics and high-Th materials, such as ejecta from the Imbrium basin. The meteorites suggest that the feldspathic upper crust of the Moon has an average Al_2O_3 concentration of 28.5 ± 1.0% Al_2O_3(Table 5), which corresponds to 79 mass%, or ~83 vol.%, plagioclase. About 10% of the iron in the feldspathic lunar meteorites, and (by inference) the surface of the highlands, derives from extralunar meteoritic material. A large fraction of that extralunar iron is in the form of metal, which may have some significance for compositional remote sensing by spectral reflectance techniques.

Feldspathic lunar meteorites vary by a factor of 3 in MgO concentration. This variation leads to a large variation in Mg', from 60 to 73. Given that all the feldspathic lunar meteorites are breccias and most are regolith breccias, a first-order conclusion from this observation is that some places on the surface of the feldspathic highlands must be considerably more magnesian (greater Mg') than others. The average Mg' of the feldspathic lunar meteorites is 70, a value similar to that of the Luna 20 regolith (71) and to the feldspathic component of the Apollo 16 regolith (70; Fig. 9a), but higher than that of typical ferroan anorthosite (50–65). Magnesian feldspathic lunar meteorites are magnesian because they contain a normative component of high-Mg' olivine ($Fo_{>80}$) that is absent if the more ferroan of the feldspathic lunar meteorites. In the most magnesian of the meteorites, the main lithologic carriers of the olivine are magnesian granulitic breccias, not mafic magnesian lithologies such as the plutonic norites, troctolites, and dunite of the Apollo collection. The most magnesian of the common feldspathic lithologies of the Apollo missions are also granulitic breccias.

The average proportion of magnesian feldspathic material (magnesian granulitic breccias and, perhaps, their unbrecciated precursors) in the surface materials of the feldspathic highlands must be large. For example, the composition (major elements) of the feldspathic upper crust estimate of Table 5 ($Mg' = 70$) corresponds well to a 57:43 mixture of MAC 88105, a ferroan feldspathic lunar meteorite ($Mg' = 63$) and Apollo 16 magnesian granulitic breccia (Table 2 of Korotev, 1997; $Mg' = 76$), suggesting subequal proportions of ferroan and magnesian feldspathic material. Semiquantitatively, this conclusion is the same as one that we made previously on the basis of europium balance (Korotev and Haskin, 1988), and we can now identify the lithologic carrier of the inferred high-Eu plagioclase as magnesian granulitic breccia or its plutonic precursors. The average composition of the magnesian granulitic breccias cannot be explained as a mixture of known plutonic rocks and they appear to be unrelated to the mafic magnesian-suite plutonic rocks of the Apollo collection (Fig. 16). We conclude that magnesian granulitic breccias derive from types of igneous or plutonic rock that are rare in the Apollo sample collection, although some of the magnesian anorthositic lithologies of the Apollo 16 and Luna 20 sites may be related. Neither the feldspathic lunar meteorites nor the magnesian granulitic breccias of the Apollo sites provide support for models involving intrusion of mafic, KREEP-bearing, Mg-rich plutons into the feldspathic crust (e.g., James, 1980; Spudis and Davis, 1986; Warren, 1988; Snyder et al., 1995; Papike et al., 1996, 1998).

The feldspathic lunar meteorites attest to a crust that is more complex than a simple ferroan anorthosite flotation cumulate. Lateral or vertical heterogeneity must exist with some portions being more magnesian that ferroan anorthosite. If the presence of magnesian feldspathic material at the present surface of the highlands is the result of vertical redistribution of crustal material by impacts, that is, if the original crust consisted of a ferroan layer overlying a magnesian layer, then feldspathic lunar meteorites and the granulitic breccias indicate two things. (1) The magnesian layer (to a depth sampled by basin-forming impacts) was only slightly more mafic (e.g., ~27% Al_2O_3, on the basis of magnesian granulitic breccias of the Apollo 16 and 17 missions; Lindstrom and Lindstrom, 1986) and (2) the magnesian layer was not substantially enriched in incompatible elements (e.g., 0.9–1.0 ppm Th; Lindstrom and Lindstrom, 1986).

All feldspathic lunar meteorites from hot deserts that we have studied (Dar al Gani 262 and 400, Dhofar 025, and Northwest Africa 482) are contaminated with certain elements from natural terrestrial weathering and human handling to degrees considerably greater than those observed in cold-desert meteorites. Among elements that we measure, those affected are K, Ca, As, Br, Rb, Sr, Sb, Cs, Ba, W, and Au. Sodium does not appear to be affected. We observe no difference in whole-rock La/Ce ratios between feldspathic lunar meteorites, either from hot or cold deserts, and Apollo samples of similar composition, with the exception that Dar al Gani 400, which has an anomalously high La/Ce ratio and may be enriched overall in light rare earth elements.

Note added in proof: Since preparation of Table 1, two new lunar meteorites from Antarctica have been announced: Pecora Escarpment (PCA) 02007, a 22.4-g basaltic breccia, and (2) LaPaz Icefield (LAP) 02205, a 1226-g crystalline mare basalt.

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