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Feldspathic lunar meteorites Pecora Escarpment 02007 and Dhofar 489: Contamination of the surface of the lunar highlands by post-basin impacts

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Abstract

PCA (Pecora Escarpment) 02007 and Dhofar 489 are both meteorites from the feldspathic highlands of the Moon. PCA 02007 is a feldspathic breccia consisting of lithified regolith from the lunar surface. It has concentrations of both incompatible and siderophile elements that are at the high end of the ranges for feldspathic lunar meteorites. Dhofar 489 is a feldspathic breccia composed mainly of impact-melted material from an unknown depth beneath the regolith. Concentrations of incompatible and siderophile elements are the lowest among brecciated lunar meteorites. Among 19 known feldspathic lunar meteorites, all of which presumably originate from random locations in the highlands, concentrations of incompatible elements like Sm and Th tend to increase with those of siderophile elements like Ir. Feldspathic meteorites with high concentrations of both suites of elements are usually regolith breccias. Iridium derives mainly from micrometeorites that accumulate in the regolith with duration of surface exposure. Micrometeorites have low concentrations of incompatible elements, however, so the correlation must reflect a three-component system. We postulate that the correlation between Sm and Ir occurs because the surface of the Feldspathic Highlands Terrane has become increasingly contaminated with time in Sm-rich material from the Procellarum KREEP Terrane that has been redistributed across the lunar surface by impacts of moderate-sized, post-basin impacts. The most Sm-rich regolith breccias among feldspathic lunar meteorites are about 3× enriched compared to the most Sm-poor breccias, but this level of enrichment requires only a few percent Sm-rich material typical of the Procellarum KREEP Terrane. The meteorite data suggest that nowhere in the feldspathic highlands are the concentrations of K, rare earths, and Th measured by the Lunar Prospector mission at the surface representative of the underlying "bedrock;" all surfaces covered by old regolith (as opposed to fresh ejecta) are at least slightly contaminated. Dhofar 489 is one of 15 paired lunar-meteorite stones from Oman (total mass of meteorite: ⩾1037 g). On the basis of its unusually high Mg/Fe ratio, the meteorite is likely to have originated from northern feldspathic highlands.

1. Introduction

Lunar meteorite PCA (Pecora Escarpment) 02007 is a 22.4-g stone collected January 5, 2003, on an ice field near the Pecora Escarpment, Antarctica. Although initially described as a basaltic breccia (McBride et al., 2003), preliminary studies showed it to be a feldspathic regolith breccia (Korotev et al., 2004; Taylor et al., 2004; Zeigler et al., 2004).

Dhofar 489, a 34.4-mg stone found in Oman on August 11, 2001, is described as a feldspathic crystalline matrix breccia (Russell et al., 2002; Takeda et al., 2006). It is unusual, compared to other feldspathic lunar meteorites and feldspathic Apollo samples, in containing clasts of highly magnesian (high Mg/Fe) feldspathic lithologies (Takeda et al., 2003, 2004a,b, 2006). It is also compositionally distinct in having lower concentrations of incompatible elements than any previously studied lunar meteorite (Karouji et al., 2004; Takeda et al., 2006). We show here that

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Dhofar stone 489 is compositionally indistinguishable from eight other Dhofar stones described as impact-melt breccias and that there are likely 15 stones with unique designations in the pair group (Table 1). For convenience, we will refer to the meteorite represented by Dhofar 489 (the first well described stone) and it pairs as "Dhofar 489 et al." in this paper, and reserve "Dhofar 489" for the stone. We have previously referred to the meteorite as "the Dhofar magnesian anorthosite" (Korotev, 2006a).

At this writing, we are aware of about 43 lunar meteorites comprising 97 named stones. The exact number of lunar meteorites is not known with certainty because pairing relationships for the newest meteorites are not well established. Of the 39 lunar meteorites for which there are compositional data, about 21 are breccias that are highly feldspathic (i.e., 25–32% Al_2O_3; Table 2) and that have low concentrations of incompatible elements (i.e., <1.8 μg/g Sm and <0.7 ppm Th). Thus, in terms of the terranes concept of Jolliff et al. (2000), about half of all lunar meteorites consist mainly of typical material of the Feldspathic Highlands Terrane. These meteorites have at most minor components of mare basalt and material of the anomalous Procellarum KREEP Terrane, the rare-earth and Th-rich geochemical anomaly in the northwest quadrant of the nearside of the Moon (Lawrence et al., 1999, 2000; Elphic et al., 2000). The two meteorites described here, PCA 02007 and Dhofar 489 et al. although both feldspathic, are very different from each other and represent, in several respects, two extremes within the feldspathic lunar highlands. As extremes, they provide information about processes that have occurred on the Moon.

In this paper, we report new compositional data for PCA 02007 and Dhofar 489 et al., as well as new petrographic data for PCA 02007. We have not yet studied the petrography of the Dhofar 489 et al. stones, but the Dhofar 489 stone has been described by Takeda Takeda et al. (2003, 2004a,b, 2006) and several of the other Dhofar 489 et al. stones have been described by Nazarov et al. (2002, 2004) and Demidova et al. (2003); PCA 02007 has been described by Day et al. (2006). Our preliminary work on the two meteorites was reported in Korotev et al. (2004), Zeigler et al. (2004), and Korotev (2006a).

Table 1
Dhofar stones likely paired with Dhofar 489

Stone	Mass of stone (g)	INAA		FB-EMPA
		N	mg	*M*
Dhofar 0303	4	2	67.3	1
Dhofar 0305	34	8	199.8	2
Dhofar 0306	13	3	87.4	1
Dhofar 0307	50			
Dhofar 0309	81	2	64.2	1
Dhofar 0310	11	6	179.4	
Dhofar 0311	4			
Dhofar 0489	34	9	284.5	
Dhofar 0730	108			
Dhofar 0731	36			
Dhofar 0908	245 (9)	4	114.7	2
Dhofar 0909	4			
Dhofar 0911	194 (9)	4	95.6	1
Dhofar 0950	22			
Dhofar 1085	197 (4)	4	107.5	1
Total	1037	42	1200.3	

The table lists the mass of each stone (with reported number of pieces, if not 1, in parentheses), the number of subsamples (*N*) and total mass (mg) used for INAA, and the number (*M*) of INAA samples pulverized and melted for "fused bead" (FB) electron microprobe analysis (EMPA).

2. Samples and analysis

2.1. PCA 02007

We were allocated four chips of PCA 02007, designated 11, 14, 16, and 28. As in our previous studies of lunar meteorites (Fagan et al., 2002; Jolliff et al., 1991, 1998; Korotev et al., 1983, 1996, 2003a,b), we broke each chip into several subsamples. For INAA (instrumental neutron activation analysis), we analyzed two subsamples of chip 11, four subsamples of chip 14, six subsamples of chip 16, and two subsamples of chip 28 for a total of 14 subsamples totaling 494 mg in mass. INAA subsample masses ranged from 20 to 45 mg and averaged 35 mg. For major-element analysis, we ground small, unirradiated subsamples of each chip (16, 21, 34, and 12 mg each from chips 11, 14, 16, and 18) into a fine powders with an agate mortar and pestle and melted 8–12 mg portions of the resulting powders on a molybdenum-strip resistance furnace to make eight "fused beads" (2, 2, 3, and 1 bead each from chips 11, 14, 16, and 18). For petrographic study, we received two polished thin sections, PCA 02007,23 (0.5 cm^2) and PCA 02007,25 (1.3 cm^2). In addition, we made a polished thick section from a portion of INAA chip 11 (0.1 cm^2).

For INAA, we prepared subsamples by breaking allocated chips with a stainless steel chisel. Subsamples and well-characterized multielement standards were encapsulated in ultrapure fused-silica tubing and irradiated for 24 h at the University of Missouri Research Reactor in a thermal neutron flux of $5 \times 10^{13}\ cm^{-2}\ s^{-1}$. We radioassayed the samples and standards by gamma-ray spectrometry on four occasions between 6 and 32 days following irradiation and used the TEABAGS programs of Lindstrom and Korotev (1982) for data reduction. Table 3 reports mean results; data for individual subsamples are reported in some of the figures.

We characterized the petrography of the PCA 02007 thin and thick sections using a combination of EMPA (electron microprobe analysis) and transmitted- and reflected-light microscopy. Quantitative analyses of mineral, glass, and lithic components of PCA 02007 were made by WDS (wavelength dispersive X-ray spectroscopy) with a JEOL 733 Superprobe at an accelerating voltage of 15 keV. Beam currents were 20 nA for glass and plagioclase, 30 nA for pyroxene and olivine, and 40 nA oxides and metal. Electron beam diameters were 20–50 μm for glass and 1 or 10 μm for mineral analyses depending upon the size of the target minerals. We used a variety of oxide,

Table 2
List of feldspathic lunar meteorites discussed in the text

Meteorite stone [a]	Paired stones [b]	Lithology [c]	Note [d]	Sources of data [e]	Symbol [f]
Allan Hills (ALHA) 81005	None	RB		3, 10, 19, 22, 30, 31, 38	A
Dar al Gani (DaG) 262	996	RB		2, 21, 39	$
Dar al Gani (DaG) 400	None	IMB (RB?)	D	21, 39, 40	¢
Dhofar 025	301, 304, 308	RB	A	21, 34, 39	5
Dhofar 026	457–468	GB or IMB	D	4, 21, 39	6
Dhofar 081	280, 910, 1224	FB	A,B	7, 39	8
Dhofar 302	Possibly 489 et al.	IMB	B,F	42	2
Dhofar 489	303, 305, 306, 307, 309, 310, 311, 730, 731, 908, 909, 911, 950, 1085	CMB or IMB	A,B,C,D,E	11, 42	4
Dhofar 490	1084	FB (RB?)		42	9
Dhofar 733	None	GB (IMB?)		42	7
MacAlpine Hills (MAC) 88105	88104	RB	A	9, 16, 24, 31, 37	M
Northeast Africa (NEA) 001	None	RB (FB?)		8, 18, 42	#
Northwest Africa (NWA) 482	None	IMB		21, 39	%
Northwest Africa (NWA) 2200	None	IMB?		42	&
Northwest Africa (NWA) 3163	None	GB		42	§
Pecora Escarpment (PCA) 02007	None	RB		41	P
Queen Alexandra Range (QUE) 93069	94269	RB	A	17, 20, 27, 28, 32, 35, 39, 42	Q
Yamato 791197	None	RB		6, 13, 21, 23, 29, 31, 36, 38	Y
Yamato 86032	82192, 82193	FB or RB	A,D	1, 5, 11, 13, 14, 15, 21, 25, 31, 33, 38	G,H

[a] Meteorite name, with acronym used in text and figures. For paired stones the largest or best characterized stone is listed in this column. Other feldspathic lunar meteorite stones not listed here because of lack of data are the feldspathic stone of Kalahari 008/009 (Sokol and Bischoff, 2005), NWA 2995 (may prove to be more mafic), and the unnamed stone described by Yanai (2000).

[b] Other stones assumed here to be paired with stone of column 1.

[c] CMB, crystalline matrix breccia; FB, fragmental breccia; GB, granulitic breccia; IMB, impact-melt breccia; and RB, regolith breccia.

[d] (A) Most available compositional data are for the stone of column 1. (B) Pairing relationships are not well established for the Dhofar stones. (C) We assume column-2 stones are paired with Dhofar 489 on the basis of reasons described in text. (D) Different petrographers have classified the lithologic type (column 3) differently. (E) Dhofar stone 489 was found 22–24 km distant from the other stones of the assumed pairing. (F) Dhofar 302 was found in the same area as the paired stones of Dhofar 489 (e.g., Dhofar 303). Our small subsample is compositionally distinct, however; see text.

[e] (1,2) Bischoff et al. (1987, 1998); (3) Boynton and Hill (1983); (4) Cohen et al. (2004); (5,6) Fukuoka et al. (1986a,b); (7) Greshake et al. (2001); (8) Haloda et al. (2005); (9) Jolliff et al. (1991); (10) Kallemeyn and Warren (1983); (11) Karouji et al. (2004); (13) Koeberl (1988); (14,15,16,17) Koeberl et al. (1989, 1990, 1991, 1996); (18) Korotev and Irving (2005); (19,20,21) Korotev et al. (1983, 1996, 2003b); (22) Laul et al. (1983); (23, 24, 25, 27) Lindstrom et al. (1986, 1991a,b, 1995); (28) Nishiizumi et al. (1996); (29) Ostertag et al. (1986); (30,31) Palme et al. (1983, 1991); (32) Spettel et al. (1995); (33) Takahashi and Masuda (1987); (34) Taylor et al. (2001); (35) Thalmann et al. (1996); (36,37,38) Warren and Kallemeyn (1986, 1991a,b); (39) Warren et al. (2005); (40) Zipfel et al. (1998); (41) this work; (42) unpublished data of this laboratory (Korotev, 2006a,b).

[f] Symbol used in figures.

mineral, and glass standards to calibrate the WDS analyses. Results are reported in Table 4.

For the glass of the fused beads we determined major-element concentrations by EMPA using a 40–50 μm beam diameter and making 20–24 analyses per bead; mean results are reported in Table 3. The fused beads contain molybdenum at concentrations averaging 0.17 wt%; the values of Table 3 have been normalized to a Mo-free basis. In past studies where we have prepared fused beads by pulverizing and fusing the INAA subsamples (e.g., Zeigler et al., 2005) we found that concentrations of Na_2O and FeO in fused beads are typically 1–5% lower than the concentrations determined by INAA on the same material. We presume the discrepancy is due to loss of Na by volatilization and loss of Fe into the Mo metal or immiscible separation of the metal phase. Therefore we report the more accurate INAA-derived Na_2O and FeO concentrations, as well as the more precise INAA-derived Cr_2O_3 concentrations in Table 3. The concentrations of the other major elements are normalized to yield the original EMPA oxide sum. The largest source of uncertainty in our major-element analysis is sampling error associated with the small mass of material from each chip that we pulverize. For example, the largest difference in Al_2O_3 we observe between two beads from a given chip is 0.7 wt% Al_2O_3 whereas the largest difference between chips is 2.3% Al_2O_3.

We estimated the bulk composition of ~100 lithic clasts in the two PCA 02007 thin sections; mean results for different compositional groupings are listed in Table 4. Where the lithic clasts were coarse enough (crystalline impact-melt breccias and the coarsely intersertal glassy impact-melt breccias), we estimated bulk compositions by modal recombination, using the average compositions (determined by WDS analyses) and volume proportions (determined by image analyses on back-scattered electron images) of the constituent phases. For those cases where lithic clasts were too fine grained for modal recombination, we used broad beam (40–50 μm) WDS analyses to determine the bulk composition, averaging 4–5 spots per clast. In fine-grained lithic clasts that contained large

Table 3
Mean results of bulk chemical analyses of PCA 02007 and Dhofar 489 et al

		PCA 02007				Dhofar 489 et al.	
		Bulk		Fusion crust		Bulk	
		Mean	Unc.	Mean	Unc.	Mean	Unc.
SiO_2	FB-EMPA	44.8	0.5	44.35	0.10	43.40	0.19
TiO_2	FB-EMPA	0.286	0.011	0.29	0.04	0.124	0.013
Al_2O_3	FB-EMPA	26.5	0.8	26.45	0.07	27.3	0.9
Cr_2O_3	INAA	0.157	0.004	0.112	0.017	0.082	0.006
FeO_t	INAA	6.26	0.08	6.15	0.04	3.28	0.17
MnO	FB-EMPA	0.09	0.03	0.092	0.014	0.056	0.008
MgO	FB-EMPA	6.7	0.7	7.01	0.03	7.4	1.1
CaO	FB-EMPA	15.4	0.4	15.44	0.03	17.1	0.6
Na_2O	INAA	0.333	0.003	*0.16*	0.02	0.332	0.009
K_2O	FB-EMPA	0.021	0.007	*0.012*	0.002	0.021	0.005
P_2O_5	FB-EMPA	0.027	0.009	0.021	0.006	0.039	0.007
Σ		100.14		100.02		99.23	
Mg′		0.66	0.07	0.670	0.004	0.80	0.02
Sc	INAA	12.65	0.21			4.74	0.13
Cr	INAA	1075	25			540	37
Co	INAA	29.2	1.1			10.9	1.1
Ni	INAA	354	18			52	8
Sr	INAA	147	5			700	221
Zr	INAA	36	5			7	2
Ba	INAA	34	2			238	133
La	INAA	2.55	0.25			0.633	0.045
Ce	INAA	6.85	0.63			1.60	0.08
Nd	INAA	4.2	0.5			1.09	0.10
Sm	INAA	1.269	0.11			0.301	0.011
Eu	INAA	0.763	0.009			0.706	0.017
Tb	INAA	0.282	0.026			0.067	0.003
Yb	INAA	1.117	0.075			0.273	0.010
Lu	INAA	0.157	0.011			0.0399	0.0015
Hf	INAA	0.94	0.09			0.194	0.010
Ta	INAA	0.135	0.013			0.029	0.003
Ir	INAA	16.8 (14.1)	3.2 (0.4)			1.1	0.2
Au	INAA	6.7 (3.7)	5.4 (0.4)			2.8	2.1
Th	INAA	0.41	0.04			0.069	0.008
U	INAA	0.11	0.01			0.190	
Mass	mg (INAA)	493.6				1200.3	

Major- and minor-element concentrations are given in mass % (cg/g), total element as oxide. Trace element data are in μg/g (ppm), except Ir and Au are in ng/g (ppb). For PCA 02007, major-element data obtained on the fusion crust by EMPA are given. For Ir and Au, the value in parentheses represents deletion of data for one highly anomalous subsample (Fig. 11). For each stone, we first calculated a mean weighted by the analyzed mass of the individual subsamples (powders for FB-EMPA, chips for INAA). For PCA, that value is presented here. For Dhofar, we present the simple mean of the weighted means for the analyzed stones. Uncertainties (unc.), which reflect both analytical and sampling error, are 95% confidence limits based on $N = 4$ for the PCA FB-EMPA data (1 each subsample of each allocated chip), $N = 40$ (spots) for the PCA EMPA data on the fusion crust, $N = 14$ for the PCA INAA data (all analyzed subsamples), and $N = 7$ for Dhofar (FB-EMPA and INAA, all analyzed stones).

plagioclase clasts, we used a combination of broad-beam analysis (to determine matrix composition) and modal recombination (to account for excess plagioclase). For the broad-beam analyses, the two main phases making up the heterogeneous target were very-fine-grained plagioclase and glass. Because the density of the glass is not likely to differ significantly from that of plagioclase, we have not attempted to make a correction for the heterogeneity of the target (e.g., Albee et al., 1977; Nazarov et al., 1982). We note also that the bulk compositions of lithic clasts, whether determined by modal recombination or broad-beam analysis, and the compositions of glass clasts cover about the same distribution of values and have similar averages.

2.2. Dhofar stones

We acquired samples of numerous Dhofar lunar meteorites from dealers mainly for the purpose of obtaining compositional data to help establish pairing relationships among the 46 (as of August, 2006) lunar meteorite stones known from the Dhofar region of the Sultanate of Oman. All of our samples were sawn "slabs" or end cuts about 1-mm in thickness and 0.1–1 cm^2 in face area. For Dhofar stones 303, 305, 306, 309, 310, 489, 908, 911, and 1085, we subdivided the samples in 2–9 subsamples each, the number depending upon the mass of sample available, for a total of 42 subsamples averaging 29 mg in mass (Table 1). All subsamples were subjected to INAA, as for PCA 02007.

Table 4
Average and representative compositions of glass clasts and lithic clasts in PCA 02007

Type Descr. (*N*)	GC H-mafic (1)	GC H-mafic (3)	GC Mafic (20)	GC interm (12)	GC feld (20)	GC H-feld (23)	GC low-Si (4)	LC-GIM mafic (1)	LC-GIM interm (4)	LC-GIM feld (24)	LC-GIM H-feld (44)	LC-Intrgr H-feld (8)	LC-Qu H-mafic (1)	LC-Qu mafic (1)	LC-Qu mafic (1)
SiO_2	45.2	47.3	46.7	46.0	44.5	44.5	37.5	44.8	46.4	44.7	44.1	44.3	47.7	50.2	45.9
TiO_2	1.23	2.80	0.54	0.56	0.27	0.22	0.32	0.60	0.57	0.29	0.26	0.16	0.25	0.24	0.43
Al_2O_3	7.19	9.91	13.2	19.2	25.6	29.2	31.0	13.1	19.0	26.9	29.3	29.2	19.2	16.2	13.6
Cr_2O_3	0.71	0.53	0.53	0.32	0.15	0.11	0.11	0.68	0.36	0.14	0.11	0.09	0.25	0.50	0.35
FeO	26.7	20.2	15.1	10.2	6.1	4.4	5.5	15.2	10.9	5.8	4.4	3.9	11.9	13.9	18.9
MnO	0.33	0.26	0.19	0.13	0.08	0.06	0.09	0.19	0.18	0.08	0.07	0.05	0.18	0.24	0.23
MgO	13.0	7.18	12.5	10.1	8.08	5.17	7.40	12.56	9.40	6.31	4.99	5.38	7.18	7.96	10.62
CaO	6.73	10.6	10.3	11.9	14.9	16.7	17.7	9.71	12.2	15.2	16.2	16.4	13.4	10.8	9.11
Na_2O	0.22	0.29	0.08	0.25	0.20	0.22	0.06	0.06	0.32	0.34	0.35	0.31	0.30	0.20	0.14
K_2O	n.a.	0.06	<0.02	0.02	<0.02	<0.02	<0.02	<0.02	0.02	0.03	0.03	0.02	<0.02	<0.02	<0.02
P_2O_5	n.a.	0.13	0.02	0.03	0.02	<0.02	<0.02	0.02	0.02	0.05	0.03	<0.02	<0.02	0.04	<0.02
Sum	101.3	99.3	99.3	98.8	99.8	100.5	99.7	96.9	99.4	99.8	99.9	99.8	100.4	100.3	99.2
Mg'	46.6	38.7	59.6	63.9	70.4	67.6	70.6	59.6	60.5	66.0	66.7	71.1	51.7	50.6	50.1

n.a., not analyzed. The average compositions of glass clasts (GC) and lithic clasts (LC) were determined by averaging the clasts that fall into the following categories: highly feldspathic (>28 wt% Al_2O_3; H-feld), feldspathic (22–28 wt% Al_2O_3; feld), intermediate (15–22 wt% Al_2O_3; interm), mafic (10–15 wt% Al_2O_3), highly mafic (<10 wt% Al_2O_3; H-mafic), and low-Si (high-Al, silica poor; Naney et al., 1976). All of the intergranular (Intrgr) lithic clasts are averaged together, regardless of their bulk composition. Qu, quenched, *N*, number of samples in average. The LC-GIM "interm," "feld," and "H-feld" compositions were mainly determined by averaging broad-beam analyses of very fine-grained assemblages of plagioclase and glass.

For seven of the nine stones (Table 1), we acquired FB-EMPA data on one or two each of the INAA subsamples (Tables 1 and 3).

To help put compositional data for PCA 02007 and Dhofar 489 et al. into perspective, we report in some figures unpublished data that we have obtained by identical techniques for some other recently discovered feldspathic lunar meteorites for which there are little or no published data (Table 2; Korotev, 2006a,b).

3. Results

3.1. PCA 02007 petrography

PCA 02007 is a feldspathic breccia composed of mineral, glass, and lithic clasts set in a partially glassy and partially fragmental matrix (Fig. 1). Entirely glassy, clast-laden matrix occurs in a few small areas, but we did not observe discrete melt veins in our sections. Shock effects in the meteorite are minor, with maskelynite not observed, and only minor undulatory extinction or mosaicism in the mafic silicates. Our thin section of the meteorite includes a thick, vesicular fusion crust (Fig. 1). Although we did not quantitatively determine the porosity of PCA, it is similar to that of other lunar meteorite regolith breccias we have studied but less porous than many Apollo regolith breccias, similar to the findings of Warren (2001).

3.1.1. Mineral clasts

We analyzed 325 mineral clasts in PCA 02007. The analyzed clasts were predominantly plagioclase ($N = 153$),

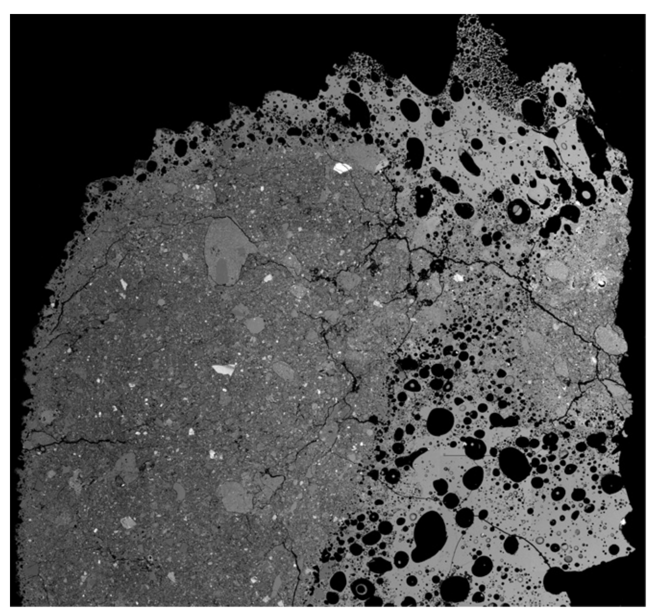

Fig. 1. Back-scattered-electron image of thin section PCA 02007,25. Darker areas are feldspar or feldspathic glass and brighter areas are Fe-rich lithologies that include pyroxene, olivine, glass, Fe,Ti oxides, and Fe,Ni metal. The vesicular area in the lower right and upper right part of the image is glassy fusion crust that apparently accumulated in a depression on the trailing side of the meteor during atmospheric entry (see whole rock photo in McBride et al., 2003).

pyroxene (98), and olivine (59). The remainder were FeNi metal, troilite, ilmenite, spinel, and silica. The relative proportions of mineral clasts analyzed does not represent a mode; plagioclase is by far the most abundant mineral clast in the meteorite, however. All of the mineral clasts in PCA 02007 are anhedral (typically angular and irregular) and range in size up to 400 μm.

The plagioclase clasts have a restricted compositional range, $An_{92–98}Or_{<0.3}$ (Fig. 2a), with only one clast outside of that range ($An_{88}Or_{0.5}$). The plagioclase is not maskelynitized, although some plagioclase clasts do show undulatory extinction. Most of the plagioclase clasts have low concentrations of FeO and MgO, with only six clasts having >0.6 wt% FeO + MgO (all <0.9 wt%). The clasts with elevated FeO or MgO have an average composition of $An_{96.7}Or_{<0.02}$.

Pyroxene and olivine clasts show considerably more compositional range than the plagioclase clasts. Pyroxene compositions ($En_{5–81}Wo_{2–43}Fs_{9–75}$) in particular, cover nearly the entire pyroxene quadrilateral (Fig. 2b). In some clasts (∼12) the pyroxene is finely exsolved, typically with augite lamellae (up to 2 μm wide) in a pigeonite host. Olivine compositions range from Fo_{41} to Fo_{82}, with most of the clasts at the magnesian end of that range (Fig. 2c). The majority of olivine clasts (48 of 58) have CaO concentrations of 0.3 wt%, consistent with derivation from nonmare rocks, with the remainder ranging up to 0.6 wt% CaO, consistent with derivation from mare basalts. The olivine clasts with elevated CaO concentrations also show a range of compositions, from Fo_{41} to Fo_{74}, also consistent with derivation from mare basalts (Ryder, 1992). Ratios of Fe to Mn are typical for lunar mafic silicates (Dymek et al., 1976; Papike, 1998), averaging 89 for olivine (range: 68–110) and 56 for pyroxene (range: 30–75). Shock effects are largely absent in pyroxene and olivine clasts, with only occasional occurrences of undulatory extinction.

Of the trace mineral clasts, FeNi metal is the most abundant. Metal grains are typically small (always <60 μm, usually <30 μm), with Ni concentrations in most grains ranging from 4 to 17 wt%, and Co concentrations from 0.2 to 0.9 wt%, that is, within the range of meteoritic metal. One meteoritic metal grain had 26.4 wt% Ni and 1.2 wt% Co. We observed several Fe-metal grains with low Ni/Co (∼1 wt% Ni and ∼0.6 wt% Co) that were not of meteoritic origin but indigenous to the Moon (Ryder et al., 1980). Most metal grains are unaltered. One large metal grain located within a vug near the edge of the section, however, is rimmed by an Fe-alteration product, most likely hematite. Metallic iron alteration products (probably hematite and goethite) also occur in fractures and void spaces surrounding the vug. This is the only terrestrial alteration effect we observed in the sample; it is evidence for limited interaction of liquid water with the sample during its residence in the Antarctic, however. Fe, Ti, and Cr oxide grains are rare and small (<50 μm). Ilmenite is the most common oxide mineral clast; rare grains of ulvöspinel, chromite, and Mg–spinel were identified by energy dispersive X-ray spectroscopy. There are two small (∼30 μm) silica clasts, both of which are associated with ferroan pyroxene. We found only one clast of symplectite (fayalite, hedenbergite, and silica).

3.1.2. Glass clasts

Most of the glass clasts analyzed ($N = 99$) are angular fragments varying in size up to 150 μm. There are a small number (6) of spherules or broken spherules (partially spherical outer edge), most of which are <50 μm across. Glass fragments and spherules range widely in composition (Fig. 3), however there is little compositional variability within any individual glass clast. The majority are feldspathic in composition (>25 wt% Al_2O_3; <7 wt% FeO), but there is a small group of moderately mafic glasses (14–16 wt% FeO; Fig. 3b). The composition of the mafic glasses (Table 4, GC-mafic) is consistent with impact glass formed from a regolith dominated by mare basalt but with some feldspathic material. Several of the most highly mafic

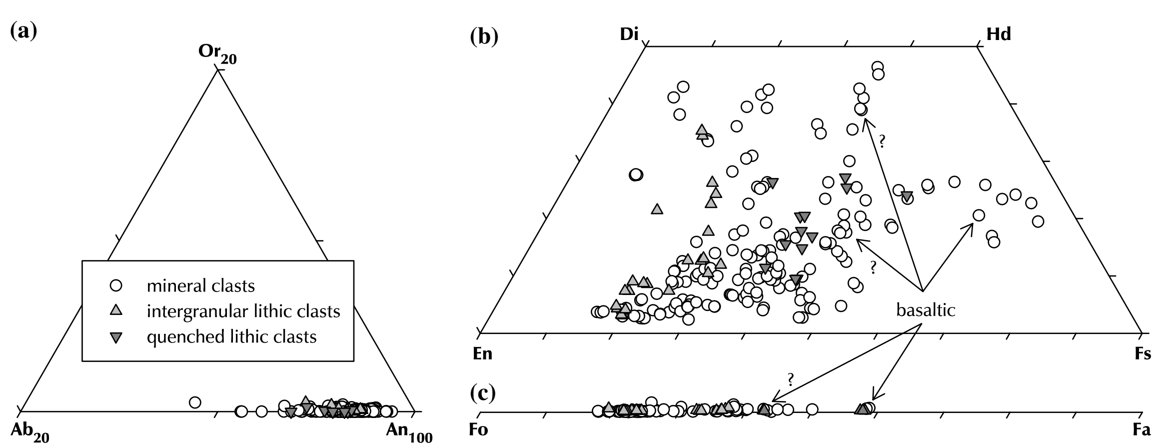

Fig. 2. Compositions of feldspar (a), pyroxene (b), and olivine (c) in mineral and lithic clasts. Mineral compositions from the glassy impact-melt breccia clasts are not included because mineral clasts are either absent (pyroxene) or the compositions are largely invariant (plagioclase and olivine). Likely or suspected minerals of basaltic origin are indicated by "?" symbol.

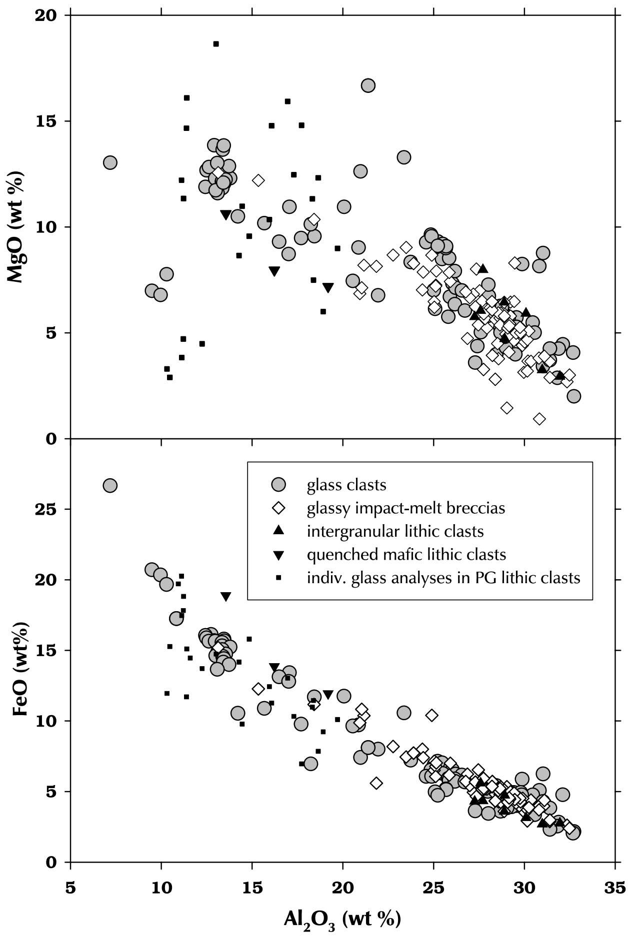

Fig. 3. Concentrations of Al_2O_3, FeO, and MgO in glass clasts, lithic clasts (whole clast), and individual spots of glass in the matrices of glassy impact-melt breccia clasts in PCA 02007. Most glasses are either highly feldspathic (>28 wt% Al_2O_3; "H-felds") or feldspathic (22–28 wt% Al_2O_3; "feld"). A few are of intermediate (15–22 wt% Al_2O_3; "interm"), mafic (a distinct cluster at 10–15 wt% Al_2O_3), or highly mafic (<10 wt% Al_2O_3; H-mafic) composition. Four high-Al, silica-poor (HASP; Naney et al., 1976) glasses are distinct as they are slightly enriched in FeO and MgO relative to other glass clasts of similar Al_2O_3 concentration. The compositional range of the individual glass analyses of glassy impact-melt breccia clasts is similar to that for the intermediate and mafic glass clasts.

glass fragments (FeO >20 wt%) contain quenched olivine crystals. All of the feldspathic glass clasts have very low concentrations of TiO_2 (<0.5 wt%); even among the moderate or highly mafic glasses only one clast has >1 wt% TiO_2 (2 wt%). Some of the highly mafic glasses have compositions consistent with low-Ti basalt. None are spherical or have compositions consistent with those of previously described lunar pyroclastic material, however, so they are unlikely to be of pyroclastic origin. Finally, four glasses have compositions that are depleted in SiO_2 and enriched in Al_2O_3 relative to other PCA 02007 glass compositions (Fig. 3). With ~36 wt% SiO_2 and ~30–31 wt% Al_2O_3, these glasses are not as extreme as the HASP (high-Al [>32 wt% Al_2O_3], silica-poor [<34 wt% SiO_2]) glasses of Naney et al. (1976) and Kempa and Papike (1980). These glasses must have undergone a similar differential volatilization process, however, because the compositions do not correspond to a mixture of lunar minerals.

3.1.3. Lithic clasts

The lithic-clast population of PCA 02007 (Figs. 4–6) consists entirely of clasts that have been modified by impacts, that is, there are no igneous lithic clasts, only clasts that have been extensively metamorphosed. The 100 clasts of this study fall into the following textural categories: glassy impact-melt breccias ($N = 84$), quenched mafic breccias (3), crystalline impact-melt breccias (8), regolith breccia (5), and agglutinates (3 or more).

The most abundant lithic clasts are glassy impact-melt breccias, which are composed of plagioclase laths with intersertal glass. We observed a few tiny (<2 μm) olivine grains (~Fo_{80}) that had nucleated from intersertal glass. Trace amounts of FeNi metal blebs (<5 μm) occur in many of these clasts. Within this group of clasts textures range from very fine grained to moderately coarse grained (Fig. 4a and b); in rare cases the amount of glass exceeds the amount of plagioclase (Fig. 4c). Large plagioclase clasts are commonly found within the glassy impact-melt breccia clasts. A small subset of the glassy impact-melt-breccia clasts have an unusual layered texture (Fig. 4d), with "layers" of plagioclase separated by "layers" of mafic glass and minor olivine. These clasts are likely the same as the "comb-textured" clasts of Day et al. (2006). The compositions of plagioclase clasts and matrix plagioclase within a given impact-melt-breccia clast are indistinguishable; both are highly calcic ($An_{96}Or < 0.1$). The composition of the intersertal glass varies widely (e.g., 7–20 wt% FeO and 3–18 wt% MgO; Fig. 3). The glass is typically mafic (15–38 wt% FeO + MgO; Fig. 3a and b) and magnesian ($Mg' =$ mole % Mg/[Mg + Fe] > 60 in almost all analyses). The bulk composition (Table 4) of these clasts is feldspathic (average Al_2O_3 concentration = 28 wt%), with >80% normative plagioclase in nearly every clast.

The second most abundant type of lithic clast has an intergranular texture (Fig. 5a and b). In transmitted light these clasts have the equant, granular texture characteristic of lunar granulitic breccias (Cushing et al., 1999). They consist dominantly of plagioclase (>80% by mode), with variable amounts of olivine, orthopyroxene, pigeonite, and augite, and trace amounts of meteoritic metal and Fe,Ti-oxides (usually ilmenite). The mafic minerals are typically magnesian ($Mg' > 70$). The plagioclase had a calcic composition ranging from An_{94} to An_{97}. The average bulk compositions of the clasts is similar to the glassy impact-melt breccia clasts. In detail the granular clasts are marginally more feldspathic and magnesian (greater Mg/Fe) than the glassy impact-melt breccia clasts, however.

The three most mafic impact-melt clasts in the sample (12, 14, and 19 wt% FeO) all have a quenched texture with no apparent clasts (Fig. 6a–c). The mineralogy is plagioclase, high-Ca pyroxene (pigeonite and augite), and sometimes olivine or Fe,Cr,Ti-oxides (chiefly chromite with minor ulvöspinel and ilmenite). The plagioclase

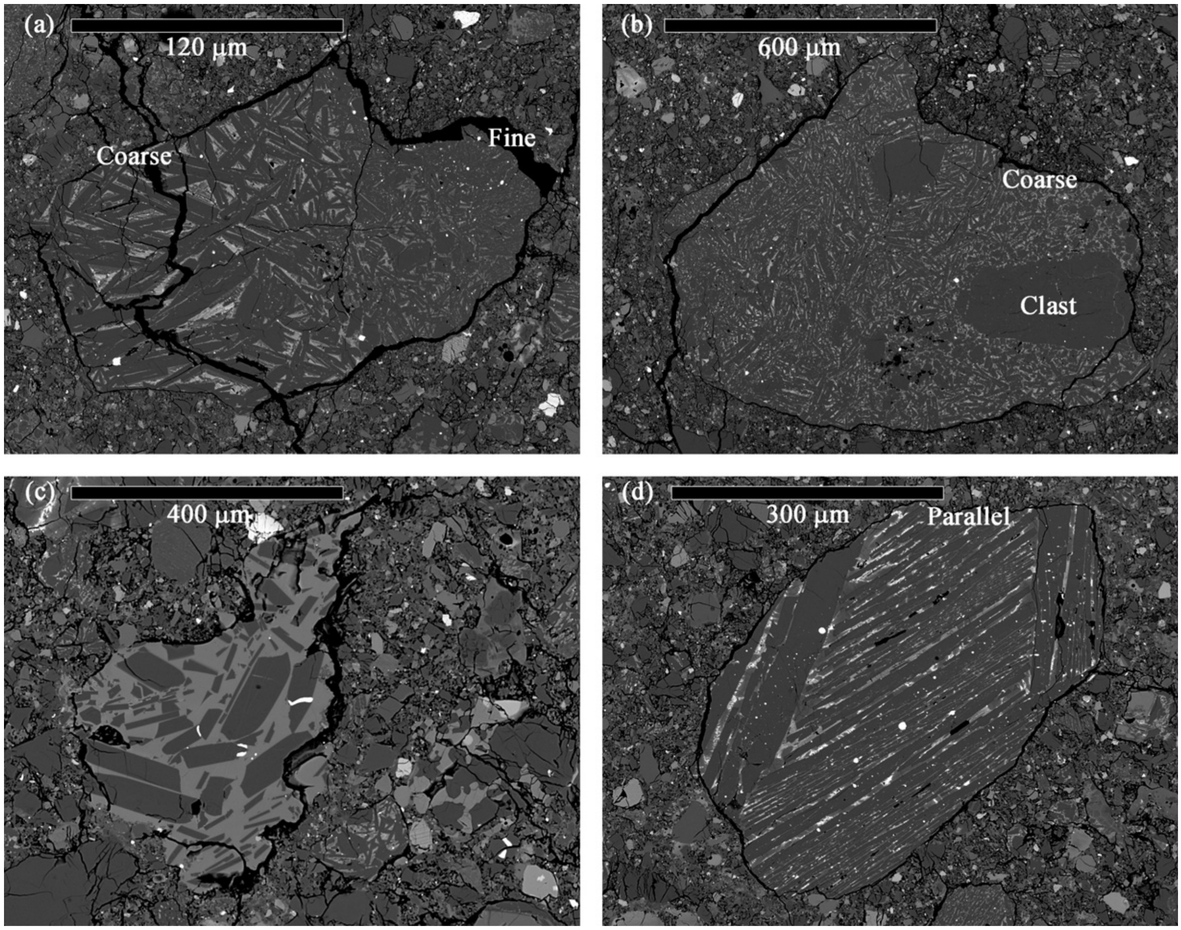

Fig. 4. Back-scattered electron images of four plagioclase-glass clasts with different textures. Plagioclase is the darker gray component of each of the clasts, with the lighter gray component being mafic glass, and the tiny white phase is usually FeNi metal, with rare occurrences of Fe,Ti oxides. (a) A glassy impact-melt breccia clast of typical size. This example illustrates the range of grain size observed within the group, from fine-grained to relatively coarse in a single clast. (b) One of the largest lithic clasts observed in PCA 02007. This glassy impact-melt breccia clast is coarse grained and has several large plagioclase clasts contained within it. (c) This glassy impact-melt breccia clast has the highest proportion of mafic glass found. The plagioclase laths are entirely (or almost entirely) isolated from one another. (d) This clast has a layered texture, with interspersed layers of plagioclase and mafic glass. The pattern repeats itself in three distinct domains within the clast.

compositions are in the range $An_{94–97}$, that is, the same as that of other plagioclase grains in the meteorite. The mafic minerals typically are more ferroan, however, than those in the other lithic clasts ($Mg' = 30–55$), suggesting that the precursor material contained a significant mare-basalt component. Several of the most mafic glass clasts also display quench crystallization effects (Fig. 6d), with olivine crystallized in a graphitic texture. We observed no unaltered clasts of mare basalt.

PCA 02007 contains a few clasts of older regolith breccias (Fig. 5c). These clasts are somewhat vesicular and have mineral, glass, and lithic fragments within them. In back-scattered electron images, clasts within the regolith-breccia clasts are more mafic (brighter) overall than the rest of the meteorite, although the composition of the mineral clasts within the regolith-breccia lithic clasts are not appreciably different from the compositions of other mineral clasts in PCA 02007. The matrices of the regolith-breccia clasts are somewhat glassy. Several large agglutinates, identified by their highly vesicular glassy matrix, occur in our thin sections. The clasts in these agglutinates are mineral fragments similar to those seen in the rest of PCA 02007. We cannot precisely determine the number of agglutinate clasts in the meteorite because it is not always possible to distinguish small agglutinate clasts from a glassy areas of the breccia matrix. There are three large agglutinate clasts, however.

3.1.4. Fusion crust

At up to 0.5 cm thickness, the fusion crust in our thin section of PCA 02007 is unusually thick and vesicular (Fig. 1). On the basis of the hand-sample description and whole-rock photos (McBride et al., 2003), the thickness appears to be the result of ablation melt collecting on the trailing side of the meteoroid during atmospheric entry. The average composition of the fusion-crust glass is similar to the bulk composition of the meteorite determined on fused beads (Table 3). The fusion crust is depleted by approximately a factor of two in Na, however, as a result of volatilization during atmospheric entry of the meteor.

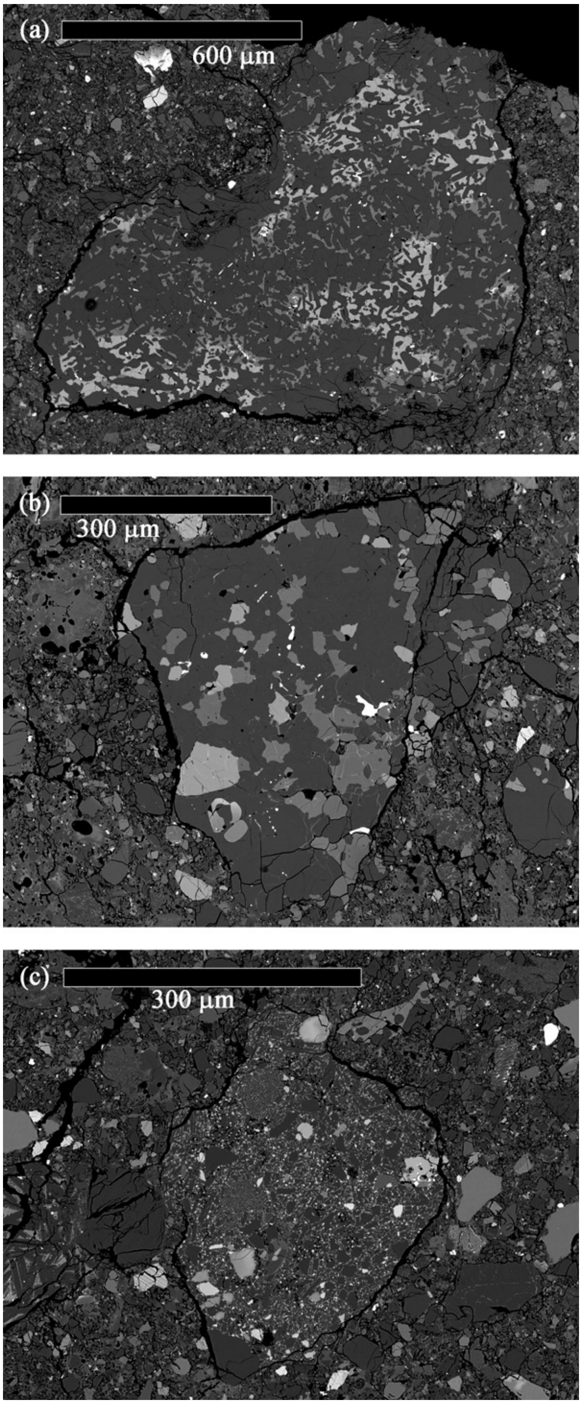

Fig. 5. Back-scattered electron images of two intergranular and one regolith-breccia lithic clasts. (a) An intergranular lithic clast with plagioclase (An_{97}; darkest phase) hosting olivine (Fo_{64}; brightest phase) and pyroxene ($En_{52–60}$ $Wo_{11–26}$ $Fs_{22–29}$; intermediate brightness). (b) A coarser-grained intergranular clast than the one in (a) but with a similar mineral assemblage: plagioclase (An_{94}) hosting olivine (Fo_{67}) and pyroxene ($En_{49–68}$ $Wo_{7–35}$ $Fs_{16–25}$; intermediate brightness). (c) A clast of an older generation of breccia that appears to be a glassy-matrix regolith breccia.

The concentration of Cr_2O_3 in the fusion crust glass is only $71 \pm 11\%$ of the concentration in the bulk meteorite. We assume the discrepancy occurs because chromium is carried in large part by heterogeneously distributed chromite and the material that melted to form the glass we analyzed was relatively depleted in Cr. (For reference, Cr_2O_3 determined in the glass of the fused beads by EMPA was $0.15 \pm 0.03\%$, compared with $0.157 \pm 0.004\%$ determined by INAA. The fusion crust averaged $0.12 \pm 0.02\%$. Uncertainties are 95% confidence limits.) Spot to spot precision, as measured by the RSD (relative standard deviation, $s/\bar{x}$), for Cr_2O_3 concentrations in the fusion crust, however, is significantly (f-test, probability >0.99) worse (48%, $N = 40$) than that for the fused beads (31%, $N = 71$).

3.2. Bulk composition

3.2.1. PCA 02007

Our compositional results for PCA 02007 are similar to those Joy et al. (2006) but differ, especially for major elements, from those of Day et al. (2006) (Fig. 7).

Concentrations of major elements in PCA 02007 lie within the range of other feldspathic lunar meteorites (Figs. 8–11). For major elements, the two parameters that vary the most among feldspathic lunar meteorites are Al_2O_3/(FeO + MgO) and MgO/FeO. The first parameter reflects the ratio of plagioclase to the ferromagnesian minerals, olivine and pyroxene. Feldspathic lunar meteorites range from about 75% to 90% normative plagioclase (Fig. 7). The second parameter reflects the olivine to pyroxene ratio because the proportion of normative olivine increases with increasing MgO/FeO in feldspathic lunar meteorites (Korotev et al., 2003b). The composition of PCA 02007 is on the mafic (high-FeO + MgO) end of the range of feldspathic lunar meteorites (Fig. 8) and the meteorite has intermediate MgO/FeO (Fig. 9). PCA 02007 has a greater concentration of Cr (1075 μg/g Cr or 0.16% Cr_2O_3) than any of the other feldspathic lunar meteorite. Like other feldspathic lunar meteorites, PCA 02007 has concentrations of incompatible elements that are low compared to feldspathic breccias of the Apollo collection (Korotev, 2005), but that are at the high end of the range for feldspathic lunar meteorites (Fig. 10a).

For lithophile elements, the 14 INAA subsamples are all similar in composition (Fig. 10). For elements associated with major mineral phases (Na, Ca, Fe, Sc, and Eu), RSDs range from 2% to 4%, at the low end of the range we have observed among brecciated lunar meteorites. Despite the small compositional range, Sc, Fe, and Cr concentrations mutually correlate, reflecting small differences in the ratio of mafic minerals to plagioclase among the subsamples. We see this effect in nearly all feldspathic lunar meteorites that we have studied. RSDs for precisely determined incompatible elements range from 12% to 18% and concentrations mutually correlate (e.g., R^2 for Sm and Th is 0.95).

Concentrations of siderophile elements in PCA 02007 (e.g., 354 μg/g Ni and 18 ng/g Ir) are high and comparable only to QUE (Queen Alexandra Range) 93069/94269 (Fig. 11) among feldspathic lunar meteorites. The mean Ir/Au ratio (3.8, excluding the two highly anomalous subsamples) falls in the range of chondritic meteorites.

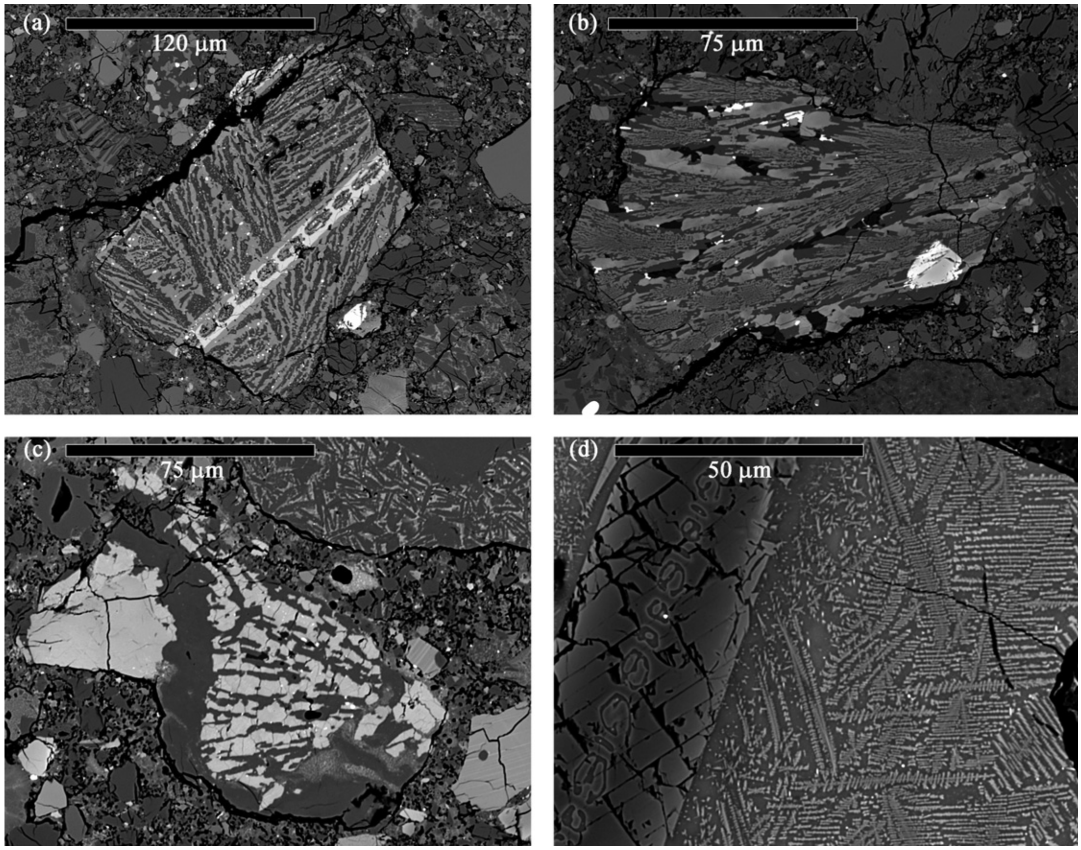

Fig. 6. Back-scattered electron images of quenched mafic lithic clasts in PCA 02007. The plagioclase-pyroxene intergrowths seen in clasts (a–c) are similar to those observed in quench crystallized basalt experiments (e.g., Lofgren, 1974). (a) With the most Fe-rich bulk composition of all of the lithic clasts (19 wt% FeO), this clast has plagioclase (An96; dark gray), pyroxene ($En_{43–48}$ $Wo_{10–26}$ $Fs_{31–43}$; gray), and olivine (Fo42; light gray), with tiny grains of Fe,Ti oxide (likely ilmenite; bright). (b) This clast has a moderately high concentration of FeO (14 wt%). The mineralogy is plagioclase (An_{97}; dark gray), pyroxene ($En_{24–47}$ $Wo_{10–27}$ $Fs_{42–52}$; light gray), silica (darkest phase), and chromite (brightest phase). (c) This clast has the lowest FeO concentration of the quenched clasts, 11 wt% FeO. It is an intergrowth of pyroxene ($En_{41–51}$ $Wo_{11–21}$ $Fs_{37–52}$; bright) and plagioclase ($An_{94–96}$; dark). (d) An example of quench crystallized olivine seen in several of the most mafic glass clasts. This clast has two generations of olivine grains, coarser, more magnesian grain (Fo76) and the very-fine grained, ferroan, graphitic olivine (Fo_{42}).

The mean Ir concentration of PCA 02007 is equivalent to a component of 2.7% ordinary chondrite or 2.8% CM chondrite. This means that 14% of the Fe and 9% of the Mg and Cr in PCA 02007 derive from extralunar sources (Figs. 8 and 9). Day et al. (2006) report an actual meteorite fragment in their thin section of PCA 02007.

As an aside we note that there are about 10 lunar meteorites, those with 15–23% Al_2O_3, that, by nonlunar-meteorite or even terrestrial standards are, in fact "feldspathic" (40–65% normative plagioclase) but which by lunar standards are intermediate. All are polymict breccias and all except Sayh al Uhaymir 169 are mainly mixtures of mare basalt and material of the feldspathic highlands ("mingled" in the terminology of Korotev, 2005). Two of these, Yamato 983885 and Dhofar 925/960, are richer in siderophile elements than PCA 02007 and other lunar meteorites. For Yamato 983885, a regolith breccia, we obtained 23 ng/g Ir in our 107-mg sample and Warren and Bridges (2004) report 22 ng/g. The meteorite would plot at 3.8% "CM chondrite equivalent" on Fig. 11. For 925/960, an impact-melt breccia, we obtain 18 ng/g Ir in our 283 mg of sample.

3.2.2. *Dhofar 489 et al.*

Dhofar stones 303, 305, 306, 309, 310, 489, 908, 911, and 1085 are compositionally indistinguishable from one another for those elements we determine by INAA that are not affected by terrestrial alteration (e.g., Fig. 12). Most of the subsamples we analyzed are strongly contaminated with U as well as Sr and Ba (Korotev, 2006a; Takeda et al., 2006) from terrestrial alteration, however. Our samples of stones 309, 489, 908, and 1085 were least contaminated. CaO/Al_2O_3 averages 0.63, compared to 0.58 for feldspathic lunar meteorites from Antarctica, suggesting that the stones contain about 2% calcite by mass.

Our whole-rock data for the nine Dhofar 489 et al. stones we studied agree well, on average, with those for Dhofar 489 of Takeda et al. (2006) obtained by inductively-coupled-plasma mass spectrometry and prompt γ-ray analysis (Figs. 7 and 12). For major-elements, however, our data are less feldspathic (lower Al_2O_3; higher FeO + MgO, Fig. 7), on average, that those of the Vernadsky group (Nazarov et al., 2002, 2004; Demidova et al., 2003; Russell et al., 2005) for "matrix glass" or "impact-melt glassy matrix" measured in thin section. We did not

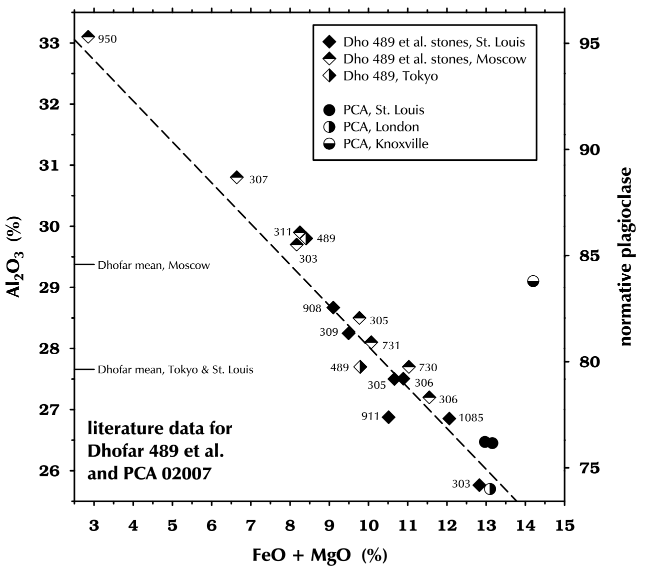

Fig. 7. For Dhofar 489 et al. (diagonal squares), the "Moscow" data represent electron microprobe analysis of "matrix glass" or "impact-melt glassy matrix" (Nazarov et al., 2002, 2004; Demidova et al., 2003; Russell et al., 2005) whereas the "St. Louis" (this work) and "Tokyo" (Takeda et al., 2006) data were obtained by whole-rock techniques. Although the two data sets do not each comprise the same set of stones, the matrix-glass (Moscow) data are substantially more feldspathic, on average, suggesting that matrix glass does not always provide an ideal proxy for bulk composition. For PCA (circles), data are from Joy et al. (2006, "London"), Day et al. (2006, "Knoxville"), and this work.

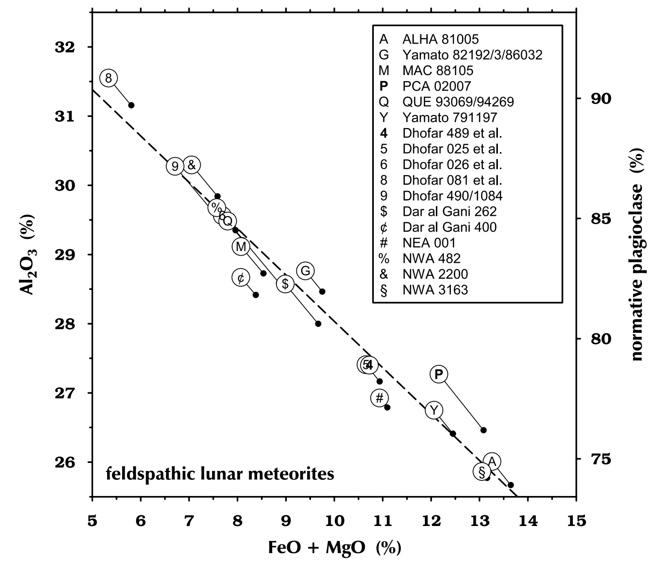

Fig. 8. Al_2O_3 anticorrelates with FeO+MgO in lunar samples, particularly polymict breccias and regoliths, because (1) the major carrier of Al, plagioclase, is poor in Fe and Mg, (2) the major carriers of Fe and Mg, pyroxene, olivine, ilmenite, and FeNi metal, are poor in Al, (3) the five phases mentioned account for 98 + % of the crystalline material in lunar samples, and (4) the mean Al_2O_3 concentration of the plagioclase and the mean FeO + MgO concentration of the non-plagioclase is rather constant among samples. As a consequence, rock compositions must plot along a mixing line between plagioclase and the Fe-bearing minerals (Korotev, 2005; Lucey et al., 2006). The small circles (some hidden) represent whole-rock compositions for each meteorite ($N = 17$). The "keyboard" points (A, 3, $, etc) represent removal of a chondritic component, assuming all Ir derives from chondrites and CM ratios of Al/Ir, Fe/Ir, and Mg/Ir for the chondritic component. Both PCA 02007 and Dhofar 489 et al. are at the mafic end of the range of feldspathic lunar meteorites (defined here as those with >25% Al_2O_3). Data for PCA 02007 and Dhofar 489 et al. are from this work; data for other meteorites from sources of Table 2. The equation of the line (dashed, simple linear regression fitted to chondrite-corrected points) is $[Al_2O_3] = -[FeO + MgO]0.670 + 34.73$ ($R^2 = 0.961$). The plagioclase axis assumes that 100% normative plagioclase = 34.73% Al_2O_3, the intercept of the line.

analyze Dhofar 307 and 950, for which the Vernadsky group obtained the most aluminous results, so it is possible that these two stones are not part of the pairing. However, the Vernadsky group obtained 29.7% Al_2O_3 for the "impact-melt matrix" of Dhofar 303 (Nazarov et al., 2002) whereas we obtained 25.8% Al_2O_3 for our bulk sample (Fig. 7), so their melt-matrix sample was distinctly more feldspathic than our whole-rock sample. The difference between the laboratories is not consistently systematic because for Dhofar 305 and 306 we obtained results very similar to those of Demidova et al. (2003) (Fig. 7).

For elements associated with major mineral phases (Na, Ca, Fe, Sc, and Eu), RSDs range from 4% to 10%, greater than for PCA 02007. RSDs for precisely determined incompatible elements range from 10% to 23% about the same as for PCA 02007.

The unusual compositional aspects of Dhofar 489 et al. ones shared by all subsamples, are the low concentrations of incompatible elements and siderophile elements (Figs. 10 and 13) and high MgO/FeO (Fig. 9) compared to all other feldspathic lunar meteorites (Takeda et al., 2006). Mean incompatible-element concentrations are 20–30% and siderophile-element (Ir) concentrations are only 18% of those of the mean we calculated three years ago for feldspathic lunar meteorites (Korotev et al., 2003b; Table 5). The mean bulk Mg' is 80%, extraordinarily high, by Apollo standards, for such a feldspathic sample (Fig. 9).

4. Discussion

4.1. Pairing

4.1.1. PCA02007

A first-order question regarding any newly discovered lunar meteorite is whether it is paired with a previously characterized stone. PCA 02007 is the first lunar meteorite to be found at the Pecora Escarpment. The next closest feldspathic lunar meteorites were found about 1150 km away, QUE (Queen Alexandra Range) 93069/94269 and MAC (MacAlpine Hills) 88104/5. The distance is large, thus it is unlikely that PCA 02007 is paired with any previously collected meteorite. For comparison, of the known paired lunar meteorites from Antarctica, Yamato 86032 was found only 2 km from Yamato 82192/3 (Takeda et al., 1989), MAC 88104 was found less than 0.5 km from MAC 88105 (Jolliff et al., 1991), EET (Elephant Moraine) 96008 was found 4 km from EET 87521 (J. Schutt, pers.

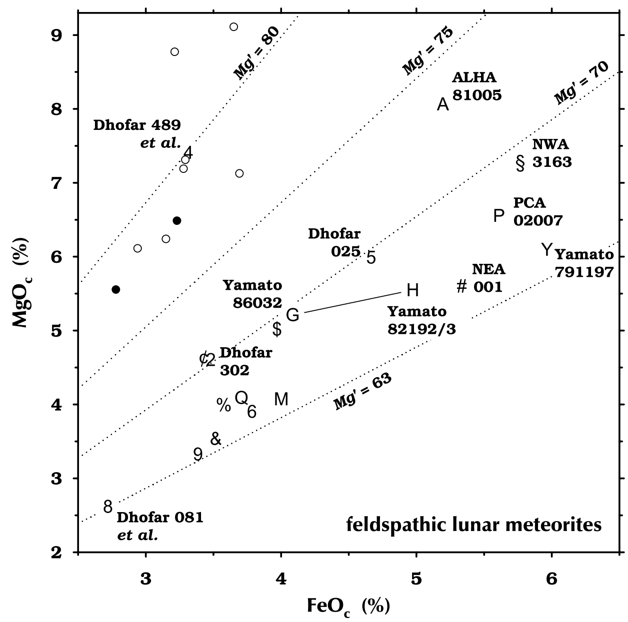

Fig. 9. The ratio of MgO to FeO varies considerably among feldspathic lunar meteorites and tends to increase with normative olivine abundance (Korotev et al., 2003b). The dotted lines represent constant *Mg'* (mole percent MgO/[MgO + FeO]). The open circles in the vicinity of Dhofar 489 et al. represent the seven stones for which major-element data were acquired for this work (303, 305, 306, 309, 908, 911, and 1085) and the filled circle represents the two bulk samples of Dhofar 489 of Takeda et al. (2006). FeO and MgO concentrations have been corrected for a chondritic meteorite component (Fig. 8). Each point represents the mean of all available data, except that data for Dhofar 489 et al. and PCA 02007 are only from this work. See Table 2 or Fig. 8 for symbol key. For comparison, *Mg'* of typical ferroan anorthosite of the Apollo collection is 60 ± 10.

comm.), and the two most distant of the five LaPaz Icefield stones were found 3 km apart (J. Schutt, pers. comm.).

PCA 02007 may be launch-paired (Warren, 1994; Korotev, 2005) with another feldspathic lunar meteorite. If so, the two meteorites likely represent locations on or near the lunar surface separated by at most a few kilometers (Warren, 1994; Head, 2001), that is, a distance comparable to traverse distances on the last three Apollo missions (15, 16, and 17). On the scale of a few kilometers, lunar soil compositions vary, but in systematic ways that reflect mixing among local rock types or regoliths (e.g., Korotev, 1987, 1991; Korotev and Kremser, 1992). Although there are only three Apollo sites with traverse distances of several kilometers for comparison, two of which were are at a mare-highlands interface, we see no compositional reason, in light of the Apollo data, to suspect that PCA 02007 is geographically related to any other feldspathic lunar meteorite. For example, although the major-element composition of PCA 02007 resembles that of Yamato 791197 (Figs. 8, 9), Cr/Sc differs significantly, with different mixing trends (Fig. 10c). Thus, there is no strong compositional evidence that PCA 02007 is launch paired with another lunar meteorite, although compositional data alone cannot exclude the possibility.

4.1.2. Dhofar stones 303, 305, 306, 307, 309, 310, 311, 489, 730, 731, 908, 909, 911, 950, and 1085 (''Dhofar 489 et al.'')

The nine Dhofar stones we studied (INAA; Table 1) are compositionally similar to each other, are together distinct from other feldspathic lunar meteorites in being more magnesian (highest MgO/FeO; Fig. 9) and having the lowest concentrations of incompatible elements and siderophile elements (Figs. 10 and 13), are texturally similar, and were found close together in the field (Fig. 14). We conclude, therefore, that they are paired. Sawn faces of the stones are distinctive in texture, with white and pink (hematite-stained) clasts having indistinct boundaries and veins of gray impact melt. On the basis of photographs of Dhofar 307, 311, 730, 731, 909, and 950 that we have seen on Internet sites of dealers and collectors and published descriptions and compositions (Nazarov et al., 2002, 2004; Demidova et al., 2003; Russell et al., 2003, 2005; Takeda et al., 2006), we suspect that these six stones are also part of the pairing. Dhofar 489, which was found 22–24 km away from the others (Fig. 14), is in no way distinct. As noted in the Introduction, we refer here to the meteorite represented by the stones as Dhofar 489 et al. only because the Dhofar 489 stone is the first to have been described in a peer-reviewed paper (Takeda et al., 2006). That many of these stones are likely paired was first recognized by Russell Russell et al. (2003, 2005), Nazarov et al. (2003, 2004), and Demidova et al. (2003), although the Dhofar 489 stone has not previously been regarded as part of the pair group.

Demidova et al. (2003) speculated on the basis of petrographic characteristics that Dhofar 305 might not be part of the pair group. We obtained samples of Dhofar 305 from two different dealers and analyzed four subsamples of each sample. The compositions of our eight Dhofar 305 subsamples are indistinguishable from the other Dhofar stones (Fig. 7), so we include Dhofar 305 in the pair group. Demidova et al. (2003) also speculated that Dhofar 302, a 3.8-g stone found near most of the Dhofar 489 et al. stones (Fig. 23), might be distinct from the others. Our sample of Dhofar 302 (87 mg, 3 subsamples) is compositionally distinct in having higher concentrations of incompatible elements (Fig. 10). Also, on the basis of the major-element data of Nazarov et al. (2002), the stone has considerably lower MgO/FeO (melt matrix: 1.20) than the same lab obtained for the nine Dhofar 489 et al. stones they analyzed (range: 1.55–1.98). (The Dhofar 302 point of Fig. 9 represents the ''impact-melt glassy matrix'' of Nazarov et al., 2002.) Thus, our working hypothesis is that Dhofar 302 represents a distinct fall from Dhofar 489 et al. It might, however, be an anomalous sample of the Dhofar 489 et al. meteorite, but there is little evidence in our subsample data that Dhofar-302-like material occurs as clasts in Dhofar 489 et al. (Fig. 10a and b).

Texturally and compositionally, the Dhofar 489 et al. stones are very different from Dhofar stones 081, 280, 910, and 1224, which are likely paired with each other (Russell et al., 2005) and which were found in the same area as most of the Dhofar 489 et al. stones (Fig. 14).

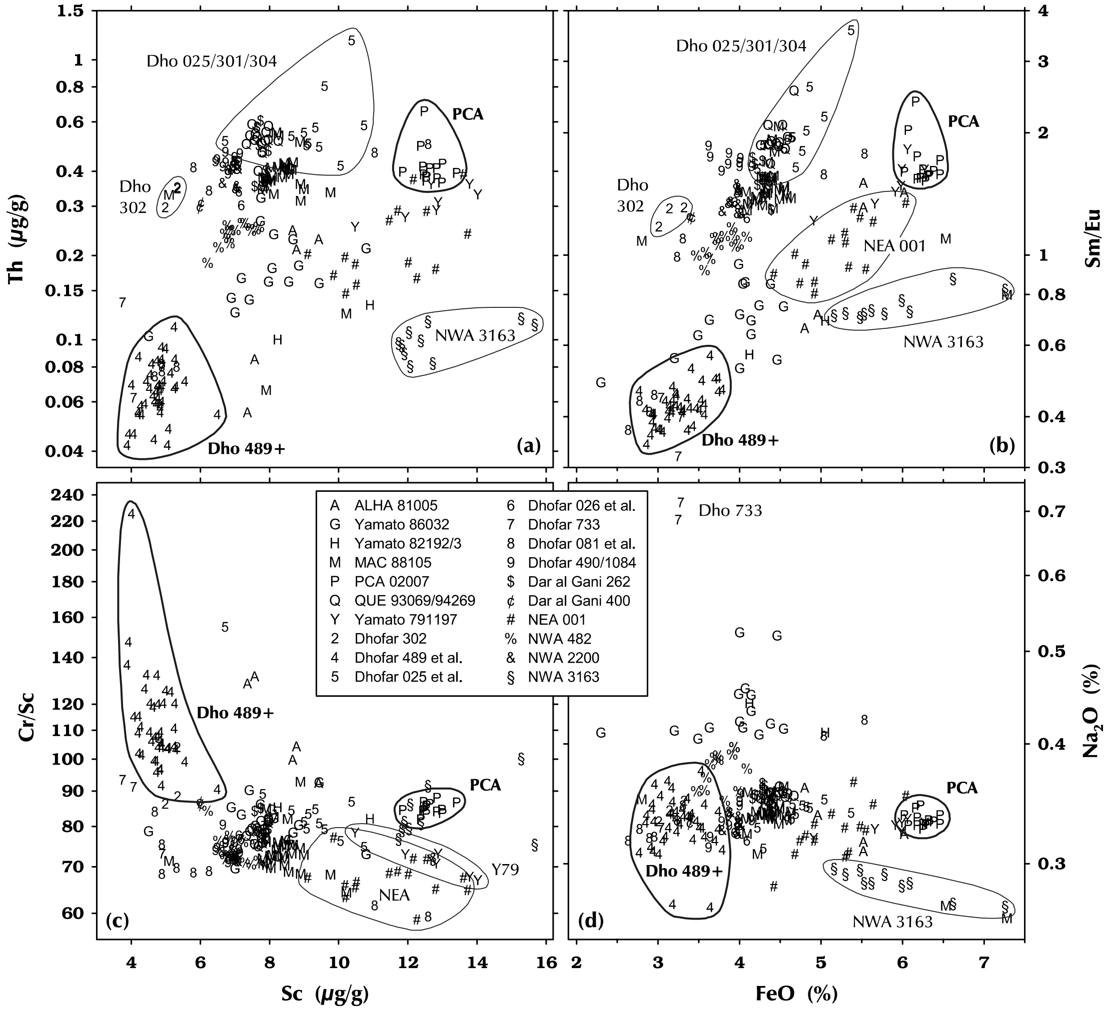

Fig. 10. INAA data for subsamples of feldspathic lunar meteorites. Clast-rich samples are excluded. The figure shows that both Dhofar 489 et al. and PCA 02007 are compositionally distinct from other feldspathic lunar meteorites. All data from this laboratory ($N = 228$; Table 2).

4.2. Correlation between incompatible elements and siderophile elements

Both PCA 02007 and Dhofar 489 et al. are breccias from the feldspathic highlands of the Moon. The two meteorites are similar to each other with respect to normative plagioclase abundance (Fig. 8). In many other respects, however, they differ significantly. (We use the term ‘‘feldspathic highlands’’ as a synonym for the Feldspathic Highlands Terrane of Jolliff et al. (2000). ‘‘Lunar highlands’’ or ‘‘the highlands’’ are ambiguous terms in that they includes regions such as the nearside Fra Mauro formation that has traditionally been regarded as ‘‘highlands’’ simply because it has not been resurfaced by mare basalt. The Fra Mauro formation lies within the topographically low and geochemically anomalous Procellarum KREEP Terrane, however, and, thus, is not closely related to the feldspathic crust that formed over most of the surface of the Moon. For this same reason, we prefer ‘‘feldspathic lunar meteorite’’ to ‘‘lunar highlands meteorite’’ [Korotev, 2005].)

The presence of glass spherules and agglutinates in PCA 02007 indicate that the stone, like many other lunar meteorites, is lithified regolith. Several lines of evidence suggest that PCA 02007 is a breccia formed from moderately mature regolith, that is, regolith for which much of the fine-grained material existed for some time at the very surface of the Moon. Cosmic-ray exposure data for PCA 02007 are consistent with moderately long surface exposure on the Moon (Nishiizumi et al., 2006). Our own data show other features associated with regolith maturity: (1) high concentrations of siderophile elements (Fig. 11), (2) vesicular fusion crust, (3) high abundance of glass fragments as clasts, and (4) uniform composition among subsamples. These features are all consistent with regolith maturity for the following reasons. With exposure at the lunar surface, regolith accumulates both micrometeorites and solar-wind implanted gases, and regolith breccias retain these components (Wasson et al., 1975; Bogard and Johnson, 1983; Korotev et al., 2003b). The gases are released as the exterior of the lunar meteoroid melts during atmospheric entry, leading to a vesicular fusion crust (Fig. 1).

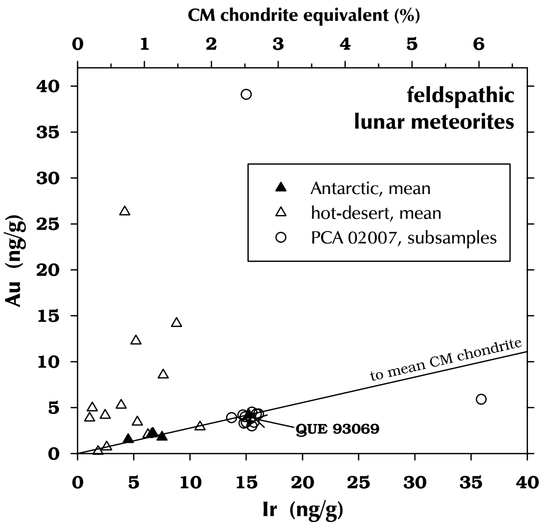

Fig. 11. Comparison of Ir and Au concentrations in subsamples of PCA 02007 (circles, this work) to mean concentrations for other feldspathic lunar meteorites (triangles, all data of this lab; each point represents a different meteorite). Hot-desert meteorites tend to be enriched in Au from contamination (handling). Among highly feldspathic lunar meteorites (>25% Al_2O_3), only QUE 93069 has an Ir concentration comparably as high as PCA 02007. One of the 14 PCA 02007 subsamples is anomalously enriched in Au and another is anomalously enriched in Ir. Such anomalies have been seen in other lunar meteorites, including those from Antarctica (Jolliff et al., 1991; Korotev et al., 1996; Warren et al., 2005). The diagonal line represents the Ir/Au ratio of CM chondrites (Wasson and Kallemeyn, 1988), the likely source of most Ir in the lunar regolith (Wasson et al., 1975). The upper scale indicates the mass-fraction equivalent of CM chondrite based on Ir concentrations.

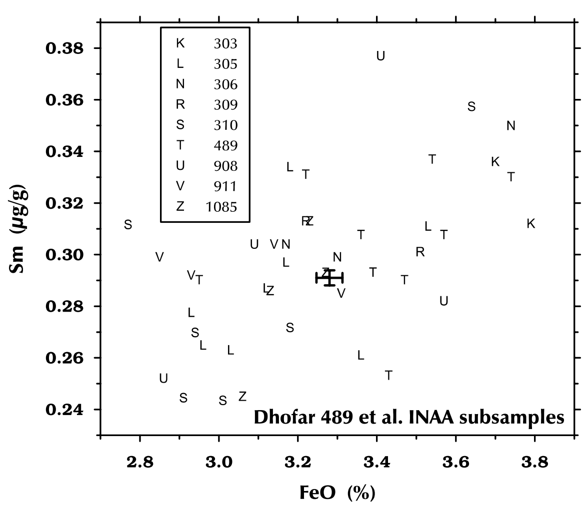

Fig. 12. FeO and Sm concentrations determined by INAA in 42 subsamples of nine Dhofar 489 et al. stones (mean mass, 29 mg; total mass, 1200 mg). For these and other elements, the various stones are indistinguishable from each other. The error bars represent ±1 standard-deviation estimates of analytical precision. The error bars are centered at the concentrations obtained for a 143-mg sample ("c") of Dhofar 489 by Takeda et al. (2006).

QUE 93069, another regolith breccia, also has a distinctive, highly vesicular fusion crust (e.g., Korotev, 2005) and is the only other feldspathic lunar meteorite with siderophile-element abundances as great as those of PCA 02007 (Figs. 11 and 13). A major product of the impact of meteoroids on the Moon is glass. Mature regolith contains a greater proportion of glass fragments than immature regolith (e.g., McKay et al., 1976). Fragments of sub-regolith rocks deposited on the surface by a moderate-sized impact (immature regolith) will experience melting by subsequent smaller impacts. The mean grain-size also decreases with duration of surface exposure (McKay et al., 1974), with the effect that small subsamples of a mature regolith are more uniform in composition than same-mass subsamples of an immature regolith because mature regolith is more well mixed. (Note the larger compositional spread in Fig. 10, compared to PCA 02007, of low-Ir, presumably immature regolith breccias NEA 001 and Dhofar 025.) In contrast, the Dhofar 489 et al. stones are described variously as a "crystalline matrix" (Takeda et al., 2006) or "impact-melt" (Nazarov et al., 2002, 2004; Demidova et al., 2003) breccias. Concentrations of cosmogenic radionuclides (Nishiizumi et al., 2004) and siderophile elements are very low, indicating that neither the meteorite nor the material from which the breccia is composed received much exposure at the surface of the Moon.

Whereas feldspathic lunar meteorites with high concentrations of siderophile elements are usually regolith breccias like PCA 02007, those with the lowest concentrations of siderophile elements are typically crystalline impact-melt and granulitic breccias like Dhofar 489 et al. (Fig. 13a). In order for impact-melt ponded in a crater to crystallize, the crater must be kilometer-scale or greater (Stöffler et al., 1979), which means the zone of melting is largely below the regolith (upper tens of meters). Intermediate are fragmental breccias, which are largely unmelted, but consist of shock-compressed fragments. By definition (Stöffler et al., 1980), fragmental breccias do not contain components such as agglutinates and glass spherules that are only produced at the lunar surface. Fragmental breccias likely form from fragmented material (megaregolith) beneath the zone where regolith breccias are produced but above the zone of melting of crystalline impact-melt breccias. Feldspathic lunar meteorites that are fragmental breccias (Table 2) tend to have intermediate concentrations of siderophile elements (Fig. 13a). Together these observations suggest that most of the siderophile elements in feldspathic lunar meteorites derive from the micrometeoroids that help form and garden the regolith (Wasson et al., 1975; Morris, 1980; Lucey et al., 2006), not from the occasional impacts of large meteoroids that form impact-melt breccias. (For the purpose of the discussion of this section, "micrometeorites" includes material from meteoroids up to several decimeters in diameter, that is, meteoroids that melt and redistribute mainly regolith. In Section 3.1.3, we note that the glassy impact-melt-breccia clasts in PCA 02007 contain blebs of FeNi metal. This metal carries at least some, perhaps much, of the Ir observed in the lunar meteorite. These clasts may have been formed from impactors larger than "micrometeoroids.")

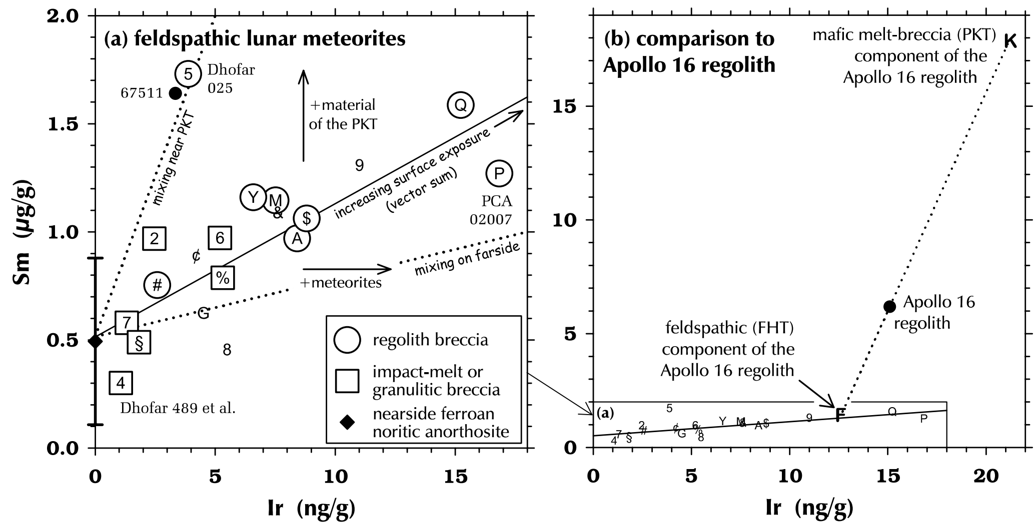

Fig. 13. (a) Among feldspathic lunar meteorites, concentrations of incompatible elements like Sm tend to be greatest in meteorites like PCA 02007 and QUE 93069 that have high concentrations of siderophile elements and are regolith breccias. Points representing meteorites classified as regolith breccias (composed of surface material) are circled; squares represent impact-melt breccias and granulitic breccias (deeper material). Others are fragmental breccias or breccias for which the type is not known or disputed. Dhofar 490/1084 (symbol 9) and NWA 2200 (&) are not well characterized and may be regolith breccias. The solid line is a simple linear regression to all points except that for Dhofar 025. $R^2 = 0.40$, or 0.67 if the Dhofar 025 is excluded. See Table 2 for symbol key. All data are from this lab. The diagonal square and error bar at zero Ir represents the mean and $\pm 2\text{-}\sigma$ range of 59 ferroan-anorthositic-suite samples from Apollo 16 that have compositions in the range of feldspathic lunar meteorites (2.5–6.5% FeO, <15 μg/g Sc, <1 ppb Ir) from the data of Haskin et al. (1981, $N = 6$) and Jolliff and Haskin (1995, $N = 53$). On average, such rocks are ferroan noritic anorthosites. The filled circle near Dhofar 025 represents Apollo 16 regolith sample 67511, an atypically feldspathic, immature sample from North Ray Crater (Korotev, 1996, and unpublished data for Ir). The dotted lines schematically represent that the vector-sum slopes are likely be greater at points near the PKT than distant from the PKT. (b) Apollo 16 regolith (circle, typical mature soil) is a mixture of mafic impact-melt breccias (K) that are rich in both incompatible and siderophile elements and material like that of the feldspathic lunar meteorites (F). Point F is a model composition representing the "removal" the melt-breccia component from the Apollo 16 regolith in the proportion (29%) required for mass balance (Korotev, 1997, 2005).

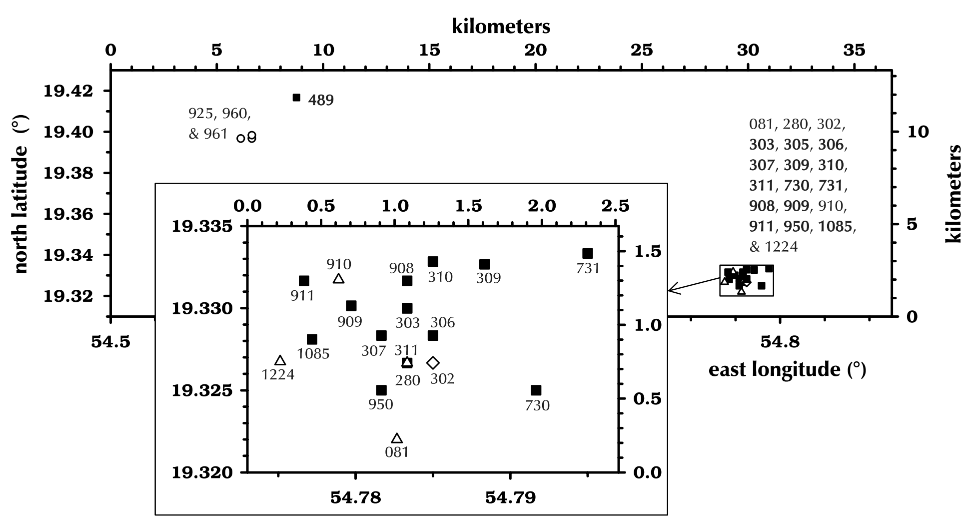

Fig. 14. Schematic map of the northern part of the region of Dhofar, Oman, meteorite finds (see Al-Kathiri et al., 2005), with locations of lunar meteorite finds. The 15 stones represented by filled squares, "Dhofar 489 et al." are compositionally indistinguishable from each other (Fig. 12) and together distinct from the others; we assume they are all paired. Stones 925, 960, and 961 are probably paired with each other and are compositionally distinct from the others in being more mafic and richer in incompatible elements (Korotev, 2006b). Stones 081, 280, 910, and 1224 are probably paired with each other but are compositionally and texturally distinct from the Dhofar 489 et al. stones (Fig. 10). Our small sample of Dhofar 302 is compositionally distinct from Dhofar 489 et al. (Fig. 10) but may be paired with it; see text. All other Dhofar lunar meteorites were found tens of kilometers to the SSW of the area of this map. All location data are from Grossman and Zipfel (2001) and Russell et al. (2002, 2003, 2004, 2005).

On the basis of data for fewer meteorites, Korotev et al. (2003b) and Nazarov et al. (2003) noted that there is a weak correlation between concentrations of incompatible elements and siderophile elements among feldspathic lunar meteorites. Our new data strengthen the correlation. Concentrations of incompatible elements tend to increase with those of siderophile elements and, therefore, surface exposure. At one extreme, PCA 02007 has among the highest concentrations of both suites of elements among feldspathic lunar meteorites and, at the other extreme, Dhofar 489 et al. has the lowest (Fig. 13a). The correlation is unexpected on the basis of 2-component mixing in that any and all types of asteroidal meteorites or interplanetary dust possibly responsible for siderophile elements in the lunar regolith have very low concentrations of incompatible elements. Another component must account for the incompatible elements, and the concentration of that component must increase with surface exposure, as do the concentration of siderophile elements and micrometeorites.

We hypothesize the following model to account for the correlation of Fig. 13a. The plutonic anorthosite of the early feldspathic lunar crust had low concentrations of both siderophile elements and incompatible elements (Warren and Wasson, 1978). For example, highly feldspathic ferroan anorthosite of Apollo 16 typically has <0.1 μg/g Sm (Haskin et al., 1981) whereas ferroan noritic anorthosites, which are more mafic and thus more similar in normative mineralogy to the feldspathic lunar meteorites, typically have 0.5 μg/g Sm (Fig. 13a). Among the feldspathic lunar meteorites, Dhofar 489 et al. best represents the plutonic rocks of the Feldspathic Highlands Terrane with regard to siderophile elements (low) and incompatible elements (0.3 μg/g Sm) because it is impact melt formed from deep material (Takeda et al., 2006).

As regolith at the surface of the feldspathic highlands accumulates micrometeorites with exposure duration, it simultaneously accumulates ejecta from impacts of "macrometeoroids," that is, meteoroids producing craters in the 1–10 km diameter range anywhere else on the Moon. Concentrations of incompatible elements are 100× greater in the rocks of the Procellarum KREEP Terrane than the plutonic rocks of the Feldspathic Highlands Terrane (Haskin et al., 2000; Jolliff et al., 2000). Thus, any impact into the Procellarum KREEP Terrane or the surrounding Imbrium ejecta deposit will produce ejecta with Sm concentrations, for example, that are several to many times greater than those of the indigenous rocks of the Feldspathic Highlands Terrane. As a consequence of mixing and entropy, concentrations of incompatible elements in regolith of the Feldspathic Highlands Terrane increases with time, on average. Locally, however, occasional large impacts lead to deposition of low-Sm material at the surface, destroying the correlation. Micrometeoroids lead directly to an increase in concentrations of siderophile elements at the lunar surface whereas impacts of occasional large meteoroids result in redistribution of lunar material that in turn leads to an increase in concentrations of incompatible elements in the regolith of the feldspathic highlands. Both processes are surface-exposure effects.

The correlation between incompatible and siderophile elements among feldspathic lunar meteorites implies that regolith at any point on the lunar surface can accumulate material from impacts at any other point. Feldspathic lunar meteorites such as PCA 02007 and QUE 93069 do not necessarily originate from locations near the Procellarum KREEP Terrane; they may originate from the farside. Their moderate enrichment in incompatible elements is a consequence of long surface exposure, not location with respect to the Procellarum KREEP Terrane. Most lunar meteorites are launched from the Moon by impacts making craters of only a few kilometers in diameter (Warren, 1994; Head, 2001; Head et al., 2002). Thus, the very existence of numerous lunar rocks on Earth, all launched from the Moon in the last 20 million years, attests to the efficacy of small impacts on the Moon in redistributing lunar material over the entire lunar surface. Even in samples of Apollo regoliths, some lithic fragments originate from points 100s of kilometers away (Zeigler et al., 2006a,b).

The fraction of Sm-rich material from the Procellarum KREEP Terrane in the feldspathic highlands is not large. The trend of Fig. 13a shows a 3-fold enrichment in Sm concentrations over the range of Ir concentrations (or 5-fold, if Dhofar 489 et al. and PCA 02007, specifically, are considered). Admixture of only a few percent material of the Procellarum KREEP Terrane to material such as Dhofar 489 et al. (0.3 μg/g Sm), however, are required to account for the concentrations of incompatible elements in regolith breccias at the high end of the trend of Fig. 13a (1.5 μg/g Sm), e.g., 4% Apollo 14 soil (30 μg/g Sm) or 1.7% of the impact-melt-breccia lithology of lunar meteorite SaU 169 (70 μg/g; Gnos et al., 2004). Thus, the regolith breccias among the feldspathic lunar meteorites suggest that moderately mature regolith anywhere in feldspathic highlands contains on the order of 1–2% material from the Procellarum KREEP Terrane and that on the scale of a Lunar Prospector resolution element (0.5°–2° of latitude and longitude), the surface concentrations of K, rare earth elements, and Th, at any location in the feldspathic highlands is at least a few times greater than that of the subregolith "bedrock." This inference, of course, would be discredited by the discovery of a feldspathic lunar meteorite that had the properties of a mature regolith breccia but which had low concentrations of incompatible elements.

The surface-exposure model we postulate is reasonable in that fragments of mare basalt have been found in nearly all the lunar meteorites that are regolith breccias. Thus proximity to exposures of mare basalt is not necessarily required for mare material to occur in feldspathic lunar meteorites (or, for that matter, basaltic lunar meteorites to occur on Earth). However, reports of "KREEPy" or K-rich lithic clasts are rarer, leading us to suspect that the carrier of the "excess" incompatible elements in highlands regoliths is mainly fine-grained impact-produced glass. We have found a type of impact glass in the Apollo 16 regolith, for example, that, with 59 ppm Sm, must derive from a point several hundred kilometers from the Apollo 16 site (Zeigler et al., 2006b) because mature Apollo 16 soil contains only about 6 μg/g Sm (Fig. 13b).

We and others have previously used the average composition of feldspathic lunar meteorites, particularly the regolith breccias, to estimate the composition of the "feldspathic upper crust." (Korotev et al., 2003b; also Palme et al., 1991). If the model described above is correct, such estimates (e.g., 1.1 μg/g Sm; Korotev et al., 2003b) overestimate the concentrations of incompatible elements by a factor of 2–3, although they do represent well the upper meter or so of regolith. We have previously assumed that feldspathic lunar meteorites are richer in incompatible elements than the "pristine" (e.g., Warren and Wasson, 1978) anorthosites of the Apollo collection because (1) feldspathic lunar meteorites are more mafic (75–90% plagioclase; Fig. 8) than most pristine ferroan anorthosites of the Apollo collection (>95% plagioclase; Haskin et al., 1981; Warren, 1990), (2) mafic, plutonic anorthosites (70–80% plagioclase, e.g., Jolliff and Haskin, 1995) are richer in incompatible elements than are highly feldspathic anorthosites (>95%, plagioclase), and (3) ferroan anorthosite and noritic anorthosite such as that of Apollo 16 is not, in fact, the dominant component of the crust of the feldspathic highlands (Korotev and Haskin, 1988; Korotev et al., 2003b). The crust of the feldspathic highlands, as we infer from the feldspathic lunar meteorites, is substantially more magnesian than ferroan anorthosite, for example (Fig. 9), indicating that not all of the plutonic rock types of the early lunar crust have been identified. Magnesian anorthosite must be an important component of the early crust and we have assumed that such anorthosites may have been intrinsically richer in incompatible elements than the ferroan-anorthositic-suite rocks of the Apollo collection. Although a breccia composed of magnesian anorthositic lithologies (Takeda et al., 2006), Dhofar 489 et al. is clearly no richer in incompatible elements than ferroan-anorthositic-suite rocks of similar plagioclase abundance (Fig. 13). Thus, we conclude from Fig. 13 that the average Sm concentration of the plutonic rocks of the early feldspathic upper lunar crust is more likely to have been 0.3–0.5 μg/g than the 1.1 μg/g estimated by of Korotev et al. (2003b) for the present "feldspathic upper crust."

4.3. *Is dhofar 489 from the farside of the Moon?*

Takeda et al. (2006) suggest that Dhofar 489 is from the farside of the Moon on the basis of the feldspathic composition and low concentration of Th and other incompatible elements in the meteorite (Fig. 10a) in comparison to the low concentrations of Fe and Th inferred or measured by the Clementine and Lunar Prospector missions for the farside surface (Lawrence et al., 2000; Lucey et al., 2000). Although it is possible that the meteorite does originate from the lunar farside, given that about half of all lunar meteorites likely originate from the farside, we stress that the feldspathic composition coupled with low Th concentration is not in itself good evidence of farside origin. Such a rock could come from anywhere in the feldspathic highlands.

Much of the surface of the nearside feldspathic highlands is contaminated with incompatible elements such as Sm and Th from the Procellarum KREEP Terrane because the last basin-forming impact to occur on the nearside, Imbrium, occurred in this geochemically anomalous area 3.9 Gyr ago, spreading Sm- and Th-rich ejecta over the surface of the Moon (Haskin, 1998; Haskin et al., 1998). Also, as argued above, post-basin impacts of smaller meteoroids have also led to contamination of the highlands surface with Th-rich material from the Procellarum KREEP Terrane. At any place in the nearside feldspathic highlands, however, most material below the Imbrium eject deposit is likely to be poor in incompatible elements because most of plutonic feldspathic rocks of the feldspathic crust had low concentrations of incompatible elements (e.g., Haskin et al., 1981; Jolliff and Haskin, 1995). Dhofar 489 was apparently formed from deep (subregolith, at least) crustal rocks (Takeda et al., 2006). Its low concentrations of incompatible elements consequently reflect depth, not necessarily distance from the Procellarum KREEP Terrane. Also, Dhofar 489 was apparently lithified (4.2 Gyr; Takeda et al., 2006) before the Imbrium impact (3.9 Gyr). It is likely that 4.2 Gyr ago, even the surface of the nearside feldspathic highlands had lower concentrations of incompatible elements than it does now. Thus, with respect only to incompatible elements, Dhofar 489 et al. could well originate from the nearside, as do the ferroan noritic anorthosites of the Apollo 16 site, which have equivalently low concentrations of incompatible elements (Fig. 13a).

Dhofar 489 et al. is highly magnesian, not ferroan, however, and on the basis of Mg/Fe ratios inferred from both the Lunar Prospector and Clementine missions (Prettyman et al., 2002; Lucey and Cahill, 2006), the meteorite is thus most likely to originate from the northern feldspathic highlands, some of which lie on the nearside.

4.4. *Are feldspathic lunar meteorites contaminated with Imbrium ejecta?*

In Section 4.3 we suggest that surface regolith of the feldspathic highlands is everywhere at least slightly (∼1%) contaminated with material of the Procellarum KREEP Terrane and that Sm- and Th-rich material accumulates in the Feldspathic Highlands Terrane with time from small, post-basin impacts into the Procellarum KREEP Terrane. Is some of the "excess" Sm (i.e., Sm in excess of the 0.3–0.5 μg/g that is characteristic of low-Ir meteorites) in the regolith breccias of Fig. 13a instead ejecta from the Imbrium basin, that is, material that has existed in the regolith for the past 3.9 Gyr? We suspect that the answer is "mostly no." The Apollo 16 regolith provides the basis for our suspicion.

The Apollo 16 site is in the feldspathic highlands near the Procellarum KREEP Terrane; the site is located on an ejecta deposit of the Imbrium basin (Cayley Plains; Muehlberger et al., 1980; Korotev, 1997). The regolith at the site is a mixture mainly of feldspathic material similar to that found in feldspathic lunar meteorites (point F, Fig. 13b) and mafic impact-melt breccias that are rich in incompatible elements (point K, Fig. 13b) and that have 3.9 Gyr crystallization ages (Duncan et al., 2004). As a consequence, Apollo 16 regolith has a greater concentration of Sm than any feldspathic lunar meteorite. The excess Sm is contributed by the ancient, Sm-rich impact-melt breccias that have existed at the site since the time of basin formation. The Apollo 16 regolith does not plot on the trend of Fig. 13a because the excess Sm is not mainly attributable to surface exposure whereas most of the Ir is, in fact, the result of surface exposure (a small fraction of the Ir, 15–20% on the basis of Fig. 13b, is contributed by the ancient melt breccias). In other words, most of the excess Sm in the regolith breccias (lunar meteorites) of Fig. 13 are post-basin additives, not syn-basin, as for the Apollo 16 regolith.

Some lunar meteorites, those with high concentrations of Sm, likely do originate from craters in the Imbrium ejecta deposit or within the Procellarum KREEP Terrane itself. These meteorites (4–72 μg/g Sm, i.e., off the scale of Fig. 13a) include, most notably, Sayh al Uhaymir 169, but also Calcalong Creek, Yamato 983885, and Dhofar 925/960/961 (Gnos et al., 2004; Warren and Bridges, 2004; Arai et al., 2005; Korotev, 2005, 2006b). All of these meteorites are less feldspathic (16–22% Al_2O_3) than those of Figs. 8 and 13 (26–31% Al_2O_3), however, because they are breccias that also contain mare basalt or mafic nonmare material of the Procellarum KREEP Terrane. (A possible alternative explanation for some meteorites with moderate enrichments in incompatible elements is that they derive from in or near the South Pole-Aitken basin, which is both more mafic and richer in incompatible elements than most of the Feldspathic Highlands Terrane, e.g., Pieters et al., 2001).

Among feldspathic lunar meteorites, anomalous Dhofar 025 has the greatest concentration of Sm, but a low concentration of Ir (Fig. 13). In this regard, it is similar to Apollo 16 sample 67511, an anomalously low-Ir (immature) and low-Sm (finite, but low melt-breccia component) regolith sample from North Ray Crater (Fig. 13a). Although 67511 contains fragments of Sm-rich impact-melt breccias (Jolliff and Haskin, 1995), no clasts with compositions similar to Sm-rich impact-melt breccias of the Apollo collection have been reported in Dhofar 025 (Cahill et al., 2004; Cohen et al., 2001; Fernandes et al., 2004). This observation leads in large part to our suggestion stated above that the lithologic carrier of the excess Sm in most feldspathic lunar meteorites is a cryptic component, like glass, created during post-basin impacts into the Procellarum KREEP Terrane. We conclude that Dhofar 025 (a regolith breccia) is enriched in Sm not because it originates from a regolith containing a significant proportion of Imbrium ejecta (as at Apollo 16, e.g., 67511) but for the same reason we propose that some other feldspathic lunar meteorites are enriched in Sm—long-distance redistribution of Sm-rich material by post-basin impacts into the Procellarum KREEP Terrane. Perhaps Dhofar 025 differs from the other feldspathic lunar meteorites of Fig. 13 because the meteorite derives from a point in the Feldspathic Highlands Terrane farther from the Procellarum KREEP Terrane than the Apollo 16 site but nearer than most of the other meteorites of Fig. 13. We can expect that the Sm/Ir slope of the line of Fig. 13a varies as a function of distance from the Procellarum KREEP Terrane (dotted lines) and that variation is one cause of the non-ideal correlation.

5. Summary and conclusions

PCA 02007 is a meteorite find from Antarctica consisting of lithified regolith from the feldspathic highlands of the Moon. In this respect it is similar to about a dozen other lunar meteorites. It is not paired with any previously described lunar meteorite because none of the others has been found near PCA 02007. We find no compositional reason to suspect that PCA 02007 and any other lunar meteorite are samples of a common regolith, that is, samples of materials that existed within a few kilometers of each other in the Moon. Thus, we find no compositional reason to suspect that PCA 02007 was launched from the same crater as that of any other feldspathic lunar meteorite. Our data cannot exclude the scenario that PCA 02007 is launch paired with another lunar meteorite, however. PCA 02007 appears to have formed from mature regolith, that is, fine-grained material that experienced considerable exposure at the lunar surface. Like Queen Alexandra Range 93069, it is rich in siderophile elements and those siderophile elements derive mainly from micrometeorites that have accumulated in the regolith as a result of surface exposure. Assuming that the siderophile-elements derive mainly from micrometeorites of CM-chondrite composition (Wasson et al., 1975), the high Ir concentration of PCA 02007 requires a 2.8% micrometeorite component. This means that 14% of the Fe and 9% of the Mg and Cr in PCA 02007 derive from extralunar sources. For incompatible elements PCA 02007 is at the high end of concentration ranges among feldspathic lunar meteorites, but concentrations are still low (e.g., 1.3 μg/g Sm) compared to feldspathic breccias of the Apollo collection.

Fifteen lunar meteorite stones from the Dhofar region of Oman are likely paired. The most well-studied of these is Dhofar 489 (Takeda et al., 2006) which was found 22–24 km from the other 14 stones. The Dhofar 489 et al. meteorite is an "impact-melt" (Nazarov et al., 2002, 2004; Demidova et al., 2003; Russell et al., 2003, 2005) or "crystalline matrix" (Takeda et al., 2006) breccia. With 27.3% Al_2O_3, Dhofar 489 et al. is similar to many other feldspathic lunar meteorites, including PCA 02007 (26.5% Al_2O_3) with respect to normative plagioclase abundance (~77%), but it is unique in several other respects. Dhofar 489 et al. has the lowest concentrations of both siderophile and incompatible elements among feldspathic lunar meteorites (this work; Takeda et al., 2006). It is more magnesian (bulk $Mg' = 80$) by far than any other feldspathic lunar meteorite and nearly any brecciated feldspathic rocks of the Apollo collection. In contrast to PCA 02007, the breccia of Dhofar 489 et al. consists mainly of material that did not acquire products of exposure at the lunar surface (micrometeorites, solar-wind implanted ions, etc.). The Dhofar 302 stone is compositionally distinct from the Dhofar 489 et al. stones. Our whole-rock data for the Dhofar 489 et al. stones is compositionally more mafic, on average, than data obtained on glassy melt matrix by others.

There is a tendency among feldspathic lunar meteorites for the regolith breccias like PCA 02007 to have greater concentrations of both incompatible and siderophile elements than the impact-melt breccias and granulitic breccias, with fragmental breccias being intermediate. The impact-melt breccias, most notably Dhofar 489, best represent the plutonic rocks of the early lunar crust with respect to these two suites of elements. Material exposed on the surface collects siderophile elements from impacts of micrometeoroids. Over the course of time it also collects ejecta from impacts of meteoroids forming craters of 1–10 km in diameter. Some of these impacts occur in the Procellarum KREEP Terrane, where concentrations of incompatible elements are on the order of 100 times greater than those of the plutonic rocks of the Feldspathic Highlands Terrane. Thus, material at the surface of the feldspathic highlands collects incompatible elements concurrently with siderophile elements and both suites of elements increase in the regolith of the feldspathic highlands with duration of surface exposure.

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