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A ferroan region of the lunar highlands as recorded in meteorites MAC88104 and MAC88105*

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Abstract—MacAlpine Hills 88104 and 88105 (MAC88104/5) are paired meteorites of noritic anorthosite composition from the lunar highlands. MAC88105 is a breccia composed mainly of melt-breccia clasts in a fine-grained, fragmental, and partly glassy matrix. The most abundant melt lithologies are feldspathic and are similar in composition to the bulk meteorite. Other melt lithologies include feldspathic melt rocks, mafic melt breccias, and a rare melt breccia relatively enriched in incompatible trace elements. Subordinate lithic clasts are granulitic breccias and ferroan (relatively low Mg/[Mg + Fe]) igneous lithologies, including troctolitic anorthosite, anorthositic norite, gabbronorite, and anorthosite. Igneous clasts having mafic mineral compositions more magnesian than Fo_{55} and En_{60} were not observed. Rare fragments of glass spheres and shards as well as glass clasts indicate that the meteorite was derived from an immature regolith. The bulk composition of MAC88105 is characterized by a molar Mg/(Mg + Fe) ratio of 0.62, at the extreme low end of the range for meteorites from the lunar highlands. Its low concentrations of incompatible trace elements and feldspathic bulk composition (29% Al_2O_3), suggest that it, like the other lunar meteorites, formed at a site far removed from the areas sampled by the Apollo missions. Similarities in mineral compositions among the different lithologies of the breccia (melt-breccia clasts, granulitic breccias, igneous fragments) and the distribution of mineral fragments suggest that most components of the meteorite were derived from a crustal section dominated by material with a noritic anorthosite composition and an affinity to the ferroan suite of plutonic rocks. The mafic melt breccias have roughly peritectic melt compositions, similar to many "low-K Fra Mauro" melt breccias in the Apollo collection but much more ferroan, and represent a source material distinct from the noritic anorthosite.

Moderate Ce anomalies, both positive and negative, occur in some separated clasts and to a lesser extent in some small chips dominated by matrix, but not in powder prepared from 20 g of bulk meteorite. These anomalies are almost certainly terrestrial weathering effects. One granulitic breccia clast is rich in siderophile elements as a result of a large amount of Fe-Ni metal. The Au/Ir ratio of the clast (0.64, CI-normalized) is distinctly different from that of metal-rich impact melts from Apollo 16 (~3, CI-normalized).

The compositional range observed among the nonmare lunar meteorites ALHA81005, Y791197, Y82192/3, Y86032, and MAC88104/5 is equivalent to that observed among representative samples of <1 mm fines from Apollo 16. Thus, compositional data provide little constraint on the number of impacts required to eject these meteorites from the Moon.

INTRODUCTION

LUNAR METEORITES MAC88104 and MAC88105 were recovered on 13 January 1989 on a blue ice field near the MacAlpine Hills, Victoria Land, Antarctica. They were found less than 0.5 km apart and strongly resembled each other in the field, although MAC88105 (662.5 g) is larger than MAC88104 (61.2 g). The recovery site (approximately 84°25'S,159°W) is about 850 km south of the Allan Hills, where the first recognized lunar meteorite was collected (ALHA81005) and about 2500 km from the Yamato Mountains, where all the other known meteorites from the lunar highlands have been found (Y791197, Y82192, Y82193, and Y86032).

We have studied a number of samples from both meteorites and report here the results of our petrographic and compositional characterization of the bulk meteorites and selected clasts. Because field relationships, macroscopic description (SCORE et al., 1989), and the data presented here confirm that MAC88104 and MAC88105 are paired, we designate the meteorites collectively as MAC88104/5. We show that MAC88104/5 exhibits some unique features compared to other lunar material.

* This paper is part of a consortium study of the largest lunar meteorite MAC88104/5.

SAMPLES STUDIED

We received samples of the meteorites from the NASA Johnson Space Center (JSC) as (1) bulk fragments (MAC88104,15 and MAC88105,35), (2) a thin section of a 1.5 cm bulk rock chip (MAC88105,80), (3) a fragment of a clast (MAC88105,51), and (4) a thin section of that clast (MAC88105,97). We also analyzed subsplits of MAC88105,41, a powder prepared from 20 g of the larger meteorite by E. Jarosewich at the Smithsonian Institution. These data are summarized in Table 1.

For chemical analysis by INAA (instrumental neutron activation analysis), we used an agate mortar and pestle to break the bulk fragments into smaller chips. During fragmentation of MAC88105,35, we separated two matrix-free subsamples of a small (~2 mm) tan-colored clast. We designated the clast C1 and the two subsamples C1A and C1B. We also separated 13 chips of "matrix-rich" material that we designated M01 through M13. These ranged in mass from about 4 to 11 mg. These samples consisted primarily of fine-grained matrix, but all undoubtedly contained small clasts. Chips that appeared to be dominated by clast material were avoided in these subsamples, but two of them, M09 and M10, contained a small portion of clast C1.

Table 1. Sample allocation data.

	split	parent	mass and description	INAA subsamples	
				matrix	clasts
MAC88105	35	11	1.044 g bulk fragments	M01-M13	C1A & C1B
MAC88105	80	22	TS of bulk		
MAC88105	51	11	0.066 g clast W2		W2A-W2F
MAC88105	97	50	TS of clast W2		
MAC88105	41	11	0.205 g powder	P1-P4	
MAC88104	15	0	0.240 g bulk fragments	M14-M17	C3-C6

Sample MAC88105,51 consisted entirely of a portion of a clast, designated W2 in the JSC documentation, exposed during sawing of the meteorite at JSC. In the documentation photo (NASA S89 47066), clast W2 appears rectangular in shape, about 7 mm in longest dimension, and lighter gray than the matrix. It was friable and arrived as numerous small chips and fines. After removing some adhering matrix material, we obtained ten relatively large, clean chips. Five of these, which we designated subsamples W2A through W2E, were analyzed individually (1.2–4.7 mg); the remaining five were combined as a single subsample designated W2F (18 mg). Sample MAC88105,97 is a thin section containing a different portion of clast W2.

Our allocation of fragments from the smaller meteorite, MAC88104,15, contained several clasts from which we prepared four samples free of matrix for INAA. Clast C3 was small and white. One large fragment of MAC88104,15 contained some small clasts as well as a 3-mm, light gray clast that broke into several pieces when the fragment was shattered. Three clast subsamples were prepared from the debris. These were designated C4, C5, and C6, although subsequent petrographic examination and results of our chemical analysis (below) indicate that clast subsamples C4 and C5 are both fragments of the light gray clast. Four "matrix-rich" chips from MAC88104,15 were also studied (M14-M17).

Four 50-mg subsplits of the powdered sample MAC88105,41 were analyzed for trace elements in order to obtain the bulk composition of the meteorite and to check for compositional uniformity of the powder. Two other subsplits of MAC88105,41 were fused for major element analysis by electron microprobe.

ANALYTICAL PROCEDURES

Procedures for INAA were similar to those described by KOROTEV (1991), but with the following modifications. Fragmental samples were irradiated for 120 h and the powdered samples were irradiated for 48 h in a thermal neutron flux of 4.9×10^{13} $cm^{-2}s^{-1}$. All samples received three or four radioassays beginning 5–6 days following irradiation. After INAA, thin sections were prepared of clast subsamples C1 and C3 through C6.

Mineral, glass, and fine-grained matrix compositions were determined with a JEOL 733 EMP (electron microprobe), using mineral and oxide standards, at an accelerating voltage of 15 keV. Feldspar analyses were done at a beam current of 20 nA, mafic silicates at 30 nA, and matrix and glass analyses at 40 nA using a broad beam (30–50 μm). Data were reduced according to the method of BENCE and ALBEE (1968). Pure metal standards were used for metal analyses and corrections were made with ZAF data reduction.

Two small subsamples of the MAC88105,41 powder were fused for major-element analysis on a molybdenum strip heater following the technique of BROWN (1977), except that the fusion was done under vacuum. The beads were analyzed by EMP using a 10 μm beam, a 30 nA beam current at 15 keV accelerating voltage, and a combination of mineral and glass standards.

RESULTS

Whole-Rock and Bulk Samples

Petrographic descriptions, clast types, and bulk compositions

Our petrographic examination of thin sections MAC-88105,80 and MAC88105,97 show that the meteorite is a feldspathic, clast-rich breccia with a glassy-fragmental matrix. Its general texture resembles those of feldspathic, glassy-matrix breccias from Apollo 16, e.g., 60019 (RYDER and NORMAN, 1980) and lunar meteorites ALHA81005, Y791197, and Y82192/3 (LINDSTROM et al., 1986; BISCHOFF et al., 1987; TAKEDA et al., 1987). The matrix (as observed macroscopically) consists of sub-rounded impact-melt breccias or glassy melt breccias ranging from 0.1 to 6 mm in diameter (Fig. 1). These breccias are generally clast-poor and have glassy or very fine-grained devitrified matrices. As observed microscopically, these and other lithic and mineral clasts (>30 μm) occur in a very fine-grained, fragmental, and partly glassy matrix. In our large thin section, MAC88105,80, the glassy melt breccias constitute about 46% of the section, the very fine-grained matrix about 38%, and the mineral, glass, and other lithic clasts 16% (Table 2). Fragments of glass and glass beads are rare, but we observed no agglutinates. Several of the glassy-melt breccias contain recognizable glass fragments, a characteristic of regolith breccias. Clast-free glass veinlets, similar in chemical composition to one reported by KOEBERL et al. (1991), transect portions of the thin section. Other lithic clasts include granulitic breccias and fragments of rocks with relict igneous textures. This distribution of clast types is sim-

Table 2. Clast population (number and volume percent) in thin section MAC88105,80 for clasts larger than 30 μm.

Component	number	%
Lithic Clasts		
Vitric and recrystallized-matrix melt breccias		
Brown vitric matrix	109	43.2
Mafic, dark matrix	17	1.1
Intersertal/subophitic melt-rocks/breccias		
Feldspathic melt rocks	15	1.4
Mafic melt rocks/basalts	4	0.3
Granulitic breccias		
Granoblastic	14	1.6
Poikiloblastic	6	2.0
Igneous fragments	22	2.5
Other	3	1.9
Mineral Fragments		
Plagioclase		6.1
Mafic minerals		1.2
Glasses		
Glass veins		0.8
Glass clasts		1.1
Matrix (<30 μm) undifferentiated		36.8

Modal analysis based on ~10000 points.

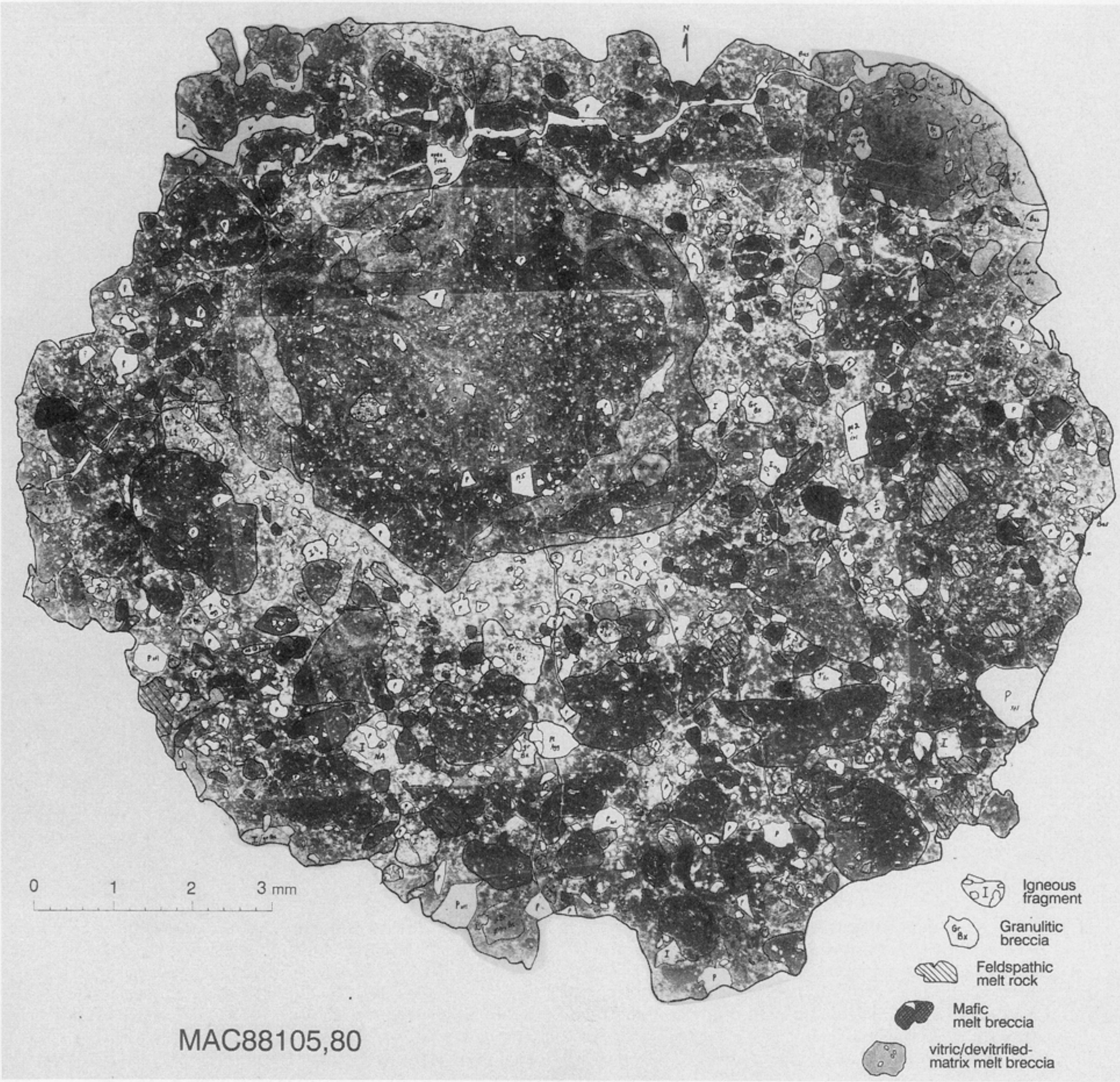

FIG. 1. Transmitted light photomosaic of thin section MAC88105,80 with overlay showing the distribution of mineral and lithic clast types. Vitric (or devitrified) matrix melt breccias are the most abundant clast type and appear darker than the fine-grained, fragmental to partly glassy matrix.

ilar to that found in MAC88105 by LINDSTROM et al. (1991), PALME et al. (1991), and TAYLOR (1991), but impact-melt breccias are not as abundant in MAC88105,80 as in MAC88105,78 (~80% by Taylor's visual estimate). The presence in MAC88105 of spherical to sub-rounded breccia clasts, glass clasts, and small clasts that may themselves be regolith breccias indicates that the meteorite is a breccia derived from the lunar regolith (cf. ALHA81005, Y791197, Y82192/3; BISCHOFF et al., 1987; TAKEDA et al., 1987).

The most abundant melt breccias are brown, clast-poor (<10 vol%) to clast-bearing (10–25 vol%), and have glassy matrices with very finely devitrified glass, very fine-grained granular and subophitic textures, and spherulitic or fibrous crystalline textures. Photomicrographs of several of the prominent clast types are shown in Fig. 2. The brown and light-brown glassy-matrix breccias are feldspathic, ranging from 24 to 30% Al_2O_3, and their matrix compositions are very similar to that of the bulk meteorite (Fig. 3a). The dark-matrix breccias are more mafic (14–17% Al_2O_3) and have matrix compositions similar to that of the peritectic in the Fo-An-Si pseudoternary system (Fig. 3a); these appear to be the same as clast types designated as "LKFM" by TAYLOR (1991) and LINDSTROM et al. (1991). One glassy melt breccia (Fig. 2e) has an intermediate bulk composition (~24 wt% Al_2O_3), but contains high concentrations of TiO_2, K_2O, and P_2O_5 (Table 3), although not as high as that of a "KREEP" clast in Y82193 described by LINDSTROM et al. (1991). A few of the glassy, melt-breccia clasts contain fine-grained,

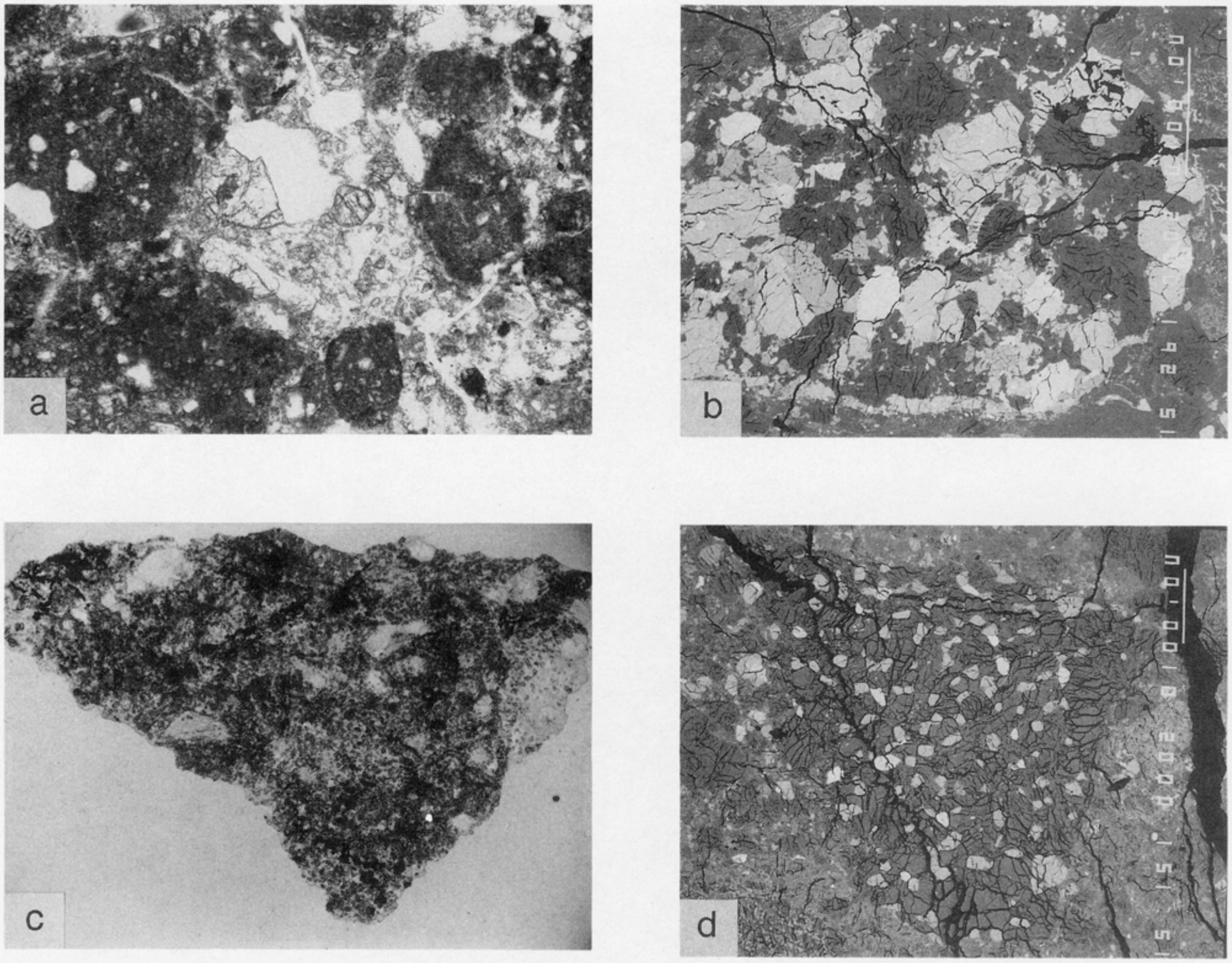

FIG. 2. Photomicrographs of representative clast types in MAC88105. In the backscattered electron images (BEIs), shadings are proportional to the average atomic number of each phase: plagioclase and feldspathic glass are dark, mafic silicates and glass are light, oxides and metal are brightest. Scale bars in the BEIs represent 100 μm. (a) Anorthositic norite clast, MAC88105,80, transmitted light, width of field: 1.6 mm; note the glassy melt breccia clasts with rounded morphologies, especially lower right-center and upper left of photo; (b) gabbronorite clast, MAC88105,97 (BEI); (c) granulitic breccia (clast C1), transmitted light, width of field: 1.6 mm; (d) granulitic breccia clast, MAC88105,80 (BEI); (e) brown, vitric-matrix melt breccia, MAC88105,80 (BEI), matrix is very finely devitrified; (f) intersertal, fine-grained feldspathic melt rock, MAC88105,80 (BEI); (g) mafic melt breccia, MAC88105,80 (BEI); (h) intergranular basalt clast, MAC88105,80 (BEI).

angular glass fragments, suggesting that these are pieces of regolith breccias. A small percentage of the rock clasts consists of other clast-free or clast-poor melt rocks (or "highland basalt") with intersertal to subophitic textures (Fig. 2f). Most of these are feldspathic (24–32% Al_2O_3, Table 3) and consist of networks of fine-grained plagioclase laths and a small proportion of mafic mesostasis. Several of the more mafic clasts may be fragments of fine-grained, very-low–Ti (VLT), volcanic basalts such as those found at Luna 24, based on EMP analyses of their minerals (Tables 4–6), crystal zoning, and intergranular texture (Fig. 2h) (cf. NEAL et al., 1991). However, these basaltic clasts are very small and we do not consider this identification to be conclusive. The glass fragments and glass vein material are very feldspathic (28–36% Al_2O_3; Table 3).

Broad-beam analyses of the fine-grained, fragmental/glassy matrix and of the most common breccias (brown glassy-matrix, mafic melt, and granulitic breccias of Table 3) yield a feldspathic average composition (~28% Al_2O_3), an average Mg′ (molar Mg/[Mg + Fe]) of ~0.59 (only slightly lower than that of the bulk meteorite), and FeO/MnO of ~60. The major-element compositions of clasts and matrix cover a range similar to those of other lunar meteorites (e.g., Fig. 4 of TAKEDA et al., 1989). Plagioclase constitutes 84% of the monomineralic clasts. Individual crystals are anorthitic (Fig. 4a, Table 4), show a range of weak shock features from undulatory extinction and some mosaicism to partial isotropization, and range in size from <30 to 800 μm. There are a few polycrystalline aggregates composed entirely or mostly of plagioclase, but most of these contain a small proportion

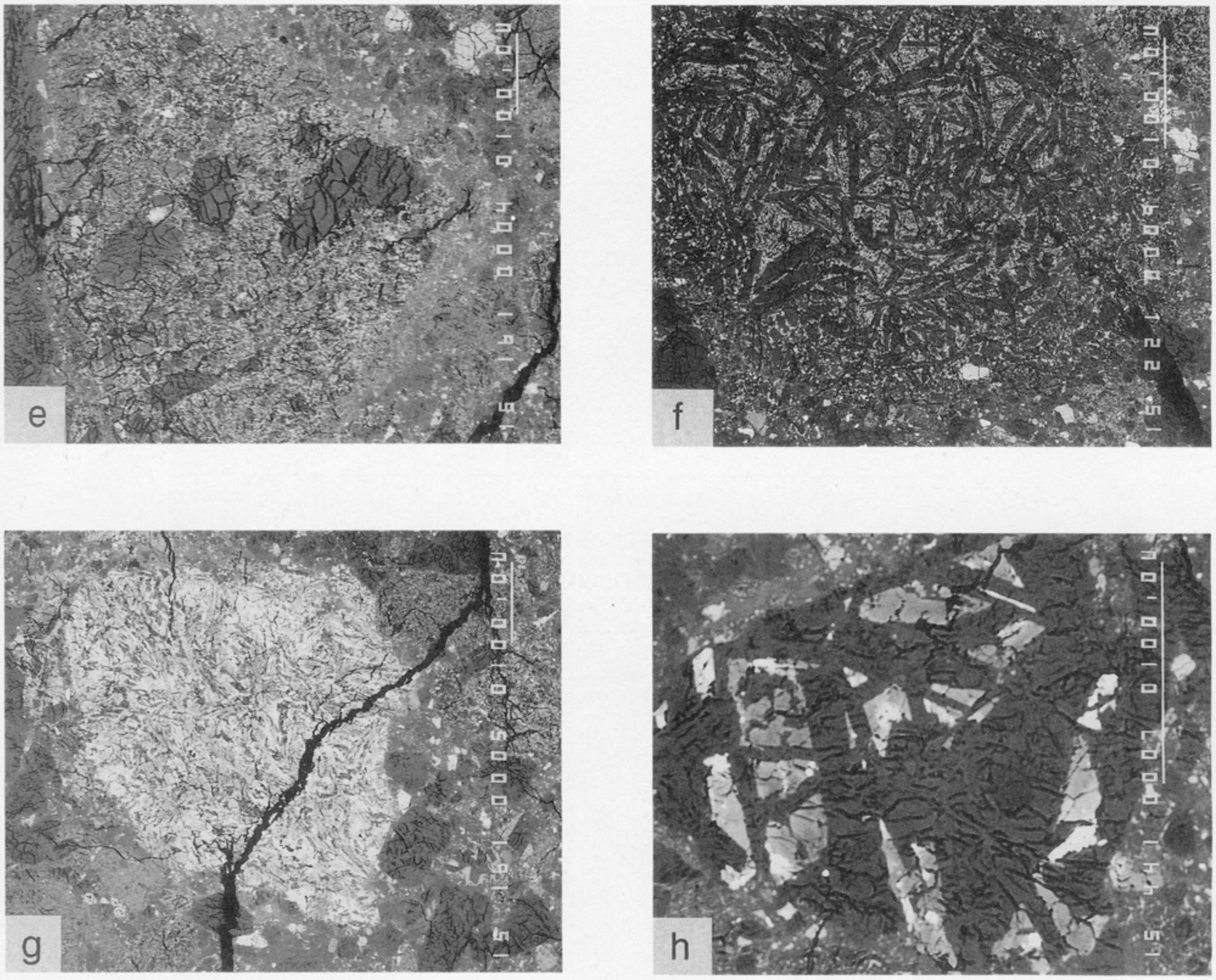

FIG. 2. (continued)

of mafic minerals. Olivine and pyroxene constitute ~15 vol% of the monomineralic clasts and range in size up to 250 μm. Although only a few of these were analyzed by EMP, the compositions span a broad range (Fig. 4b,c, Tables 5 and 6). One 200 μm clast consists of unzoned pyroxene ($En_{51}Wo_{2.6}$) intergrown with ilmenite.

Rare lithic clasts include feldspathic granulite (granoblastic texture), granulitic breccia (poikiloblastic texture), and several igneous lithologies with mineral compositions typical of rocks of the ferroan anorthosite suite of lunar plutonic rocks (WARREN, 1990) (Figs. 4 and 5). These are described below in the section on clasts.

Chemical compositions

The bulk composition of MAC88105, based on analyses of the powdered samples and matrix-rich chips (Tables 3 and 7), is similar to the average of the glassy-matrix breccias that dominate the "matrix" of MAC88105 (Fig. 3a). The whole-rock major element concentrations of MAC88105 correspond to a normative mineralogy of 81 wt% plagioclase (85 vol%), 4% diopside, 13% hypersthene, and 2% olivine; thus, the meteorite has the bulk composition of a noritic anorthosite.

The composition of MAC88104/5 falls generally in the range of other meteorites from the lunar highlands; however, the Na_2O-FeO plot of Fig. 6 shows that it is distinct. Concentrations of elements associated with mafic mineral phases (Fe, Sc, Cr) in MAC88104/5 are at the low end of the range for nonmare lunar meteorites. Concentrations of ITEs (incompatible trace elements) are at the high end of that range but, nonetheless, are low compared with regolith samples from the Apollo missions (Fig. 7). At 0.62, Mg′ is at the low end of the range observed in nonmare lunar meteorites and comparable only with Y791197 (WARREN et al., 1989).

Matrix-rich chips. Each matrix-rich chip contains a variety of clasts that were too small to avoid during sampling; thus, the chips vary in composition. The magnitude of the variation is generally similar to that observed for matrix-rich subsamples from other lunar meteorites, but is smaller than that for a suite of chips of similar mass from Y86032 (Fig. 6). For all elements, the range of compositions observed among the 13 matrix-rich chips from MAC88105 overlaps the range of the

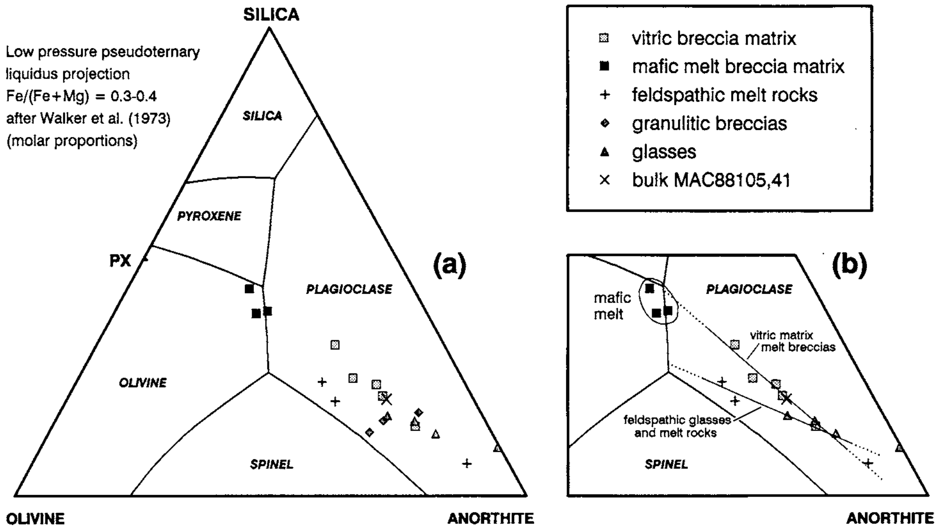

FIG. 3. (a) Compositions of matrix materials of melt-breccia lithic clasts and glasses in MAC88105,80 plotted on the Fo-Si-An pseudoternary projection. Data for lithic clasts are averages of broad-beam analyses by electron microprobe; bulk composition of MAC88105 is based on analyses of fused beads (Table 3). (b) Detail showing compositional trends defined by the different types of matrix materials of melt-breccia lithic clasts and glasses. Lines are visual fits to the data. Data for the granulitic breccias are excluded; because of their relatively heterogeneous textures, these are probably the most imprecisely determined by broad beam analysis. The feldspathic glass near the An-Si join plots at nearly the same position as plagioclase in 60025 ferroan anorthosite (e.g., WALKER et al., 1973). The trend of the vitric-matrix breccias extrapolates not toward ferroan anorthosite, but toward a more troctolitic (olivine-normative) composition.

4 matrix-rich chips from MAC88104 (Table 7, Fig. 6). The mean compositions of samples from the two meteorites are very similar (Table 7). Concentrations of ITEs average 3–4% greater for the MAC88105 samples, but this is insignificant considering the scatter. Thus, there is no indication in the compositional data that the two specimens are pieces of different falls.

Uniformity of powdered samples. The replicate analyses of the powdered samples allow testing the compositional uniformity of the powder. INAA results for the four 50-mg powdered subsamples of MAC88105, along with means ($\bar{x}$), sample standard deviations (s), and RSDs (relative standard deviation = $s/\bar{x}$, in percent) are listed in Table 7. The standard deviations reflect both analytical precision and any possible nonuniformity of the powder. For a number of elements (Na, Sc, Cr, Fe, Co, La, Ce, Sm, Eu, and Yb), we would expect RSD values of <1% for replicates of truly uniform samples with concentrations such as those observed in MAC88105, based on counting statistics and our experience with replicate analysis of homogeneous materials. For all of these elements except Cr, RSD values do not exceed 1% (range: 0.30% for Sc to 0.85% for Co). For Cr, the value is only slightly greater, 1.2%, but it is clear that this is caused by a single subsample, P2; the other three subsamples have nearly identical Cr concentrations while that for P2 is 2.3% greater. Thus, there is probably a Cr-rich phase (possibly contamination, e.g., stainless steel) that is not uniformly dispersed among the 50-mg subsamples. Among the remaining elements (those with RSD > 1%), the only ones for which the standard deviation significantly exceeds that expected on the basis of counting statistics are Ir and Th (F-test, 95% confidence). For Th, we expect that part of the scatter results from analytical imprecision not associated with counting statistics (photopeak integration error); thus, we do not take these results as strong evidence that 50-mg samples of the MAC88105,41 powder are inhomogenous for Th. However, the scatter for Ir is almost certainly caused by nonuniform distribution of Ir-rich phases, probably metal of extralunar meteoritic origin. For the most precisely determined siderophile element, Ni, the RSD is only 3.8%, which is not significantly different from that which we would expect from counting statistics alone (6.2%).

Overall, the results indicate that for 50-mg subsamples, the abundances of most elements in the MAC88105,41 powder are uniform within our analytical ability to distinguish differences. This allows us to conclude, for example, that the 4.6% difference between the Sm concentration obtained here (1.20 μg/g) and that obtained by WARREN and KALLEMEYN (1991) on a subsample of the same powder (1.15 μg/g, 317 mg sample) is not the result of sampling variation in the powder but the result of a systematic interlaboratory bias.

For all elements except Au, the mean concentrations for the four powdered samples (total mass: 193 mg) agree well with weighted mean concentrations of the 17 matrix-rich chips (110 mg), usually within 2% for the high-precision, compatible elements. Concentrations of ITEs average ~5% greater in the powder, but this is insignificant compared to the range of concentrations observed among the individual chips. For Au, the powder averages 0.9 ng/g greater than the matrix chips; this difference is significant at the 99% confidence interval (t-test). Although this is a small absolute difference, the relative difference is large (powder/matrix-rich chips = 1.5). This difference is not the result of a greater proportion of extralunar meteoritic material in the powder because the Ni concentrations are the same (Fig. 8). The mean Au/Ni ratio of the matrix-rich chips is within error of the CI average, that for the powder is higher (Fig. 8). Thus, the powdered sample may be slightly contaminated with gold. Similar differences in Au concentration between chips and the powder were obtained by PALME et al. (1991) and WARREN and KALLEMEYN (1991).

Clasts

The meteorite contains numerous clasts and we studied several of them in detail. Clast subsamples designated C1 and C3 through C6 (Table 1) were analyzed by INAA and subsequently studied in thin section. For clast W2, the INAA subsamples (W2A-W2F) are different from the thin section sample. Other clasts discussed below were studied only in thin section. Of those clasts analyzed by INAA, EMP analysis was done on clasts C1 and W2 only.

Table 3. Compositions of bulk powder, matrix of impact melt clasts, granulitic breccias, and glasses in MAC88105,41, MAC88105,80, and MAC88105,35 C1.

	88105,41 powder	brown glassy-matrix breccias					vein glass	feldspar glass	glass fragment	glass bead
(n):	(7)	(3)	(3)	(3)	(5)	(5)	(2)	(1)	(1)	(1)
Note:	A	B				D				
SiO_2	45.33	43.58	44.45	44.71	45.01	45.77	44.55	44.07	43.76	43.74
TiO_2	0.24	0.21	0.48	0.23	0.51	1.12	0.25	0.02	0.10	0.20
Al_2O_3	28.97	30.46	27.31	27.60	25.71	24.13	30.83	35.63	30.98	28.23
Cr_2O_3	0.09	0.06	0.09	0.07	0.18	0.17	0.06	0.01	0.12	0.12
FeO	4.32	3.28	4.58	4.68	5.96	6.37	3.32	0.13	1.86	5.09
MnO	0.06	0.05	0.05	0.09	0.10	0.08	0.05	0.02	0.01	0.05
MgO	3.89	3.08	3.91	3.64	4.76	5.17	3.03	0.04	2.65	3.67
CaO	16.72	17.06	15.96	16.95	15.66	14.26	17.29	19.15	18.25	16.62
Na_2O	*0.27*	0.26	0.39	0.31	0.35	0.57	0.30	0.32	0.18	0.11
K_2O	0.03	0.01	0.07	0.01	0.01	0.16	0.03	n.d.	<0.01	0.02
P_2O_5	0.08	0.04	0.09	0.02	<0.02	0.23	<0.03	n.d.	<0.03	<0.03
Sum	100.0	98.1	97.4	98.3	98.3	98.0	99.7	99.4	97.9	97.9
Mg′	0.62	0.63	0.60	0.58	0.59	0.59	0.62	0.33	0.72	0.56

	mafic melt breccias			feldspathic melt rocks			granulitic bx		clast C1 matrix	clast C1 bulk
(n):	(3)	(3)	(2)	(4)	(2)	(5)	(3)	(2)	BB (8)	FB (3)
Note:			E			F			C,G	C
SiO_2	47.82	47.29	48.55	42.61	44.20	44.85	44.02	43.20	43.08	43.61
TiO_2	0.85	0.87	1.31	0.07	0.31	0.18	0.09	0.36	0.21	0.43
Al_2O_3	17.43	16.44	14.43	32.50	25.47	24.56	30.59	28.17	28.55	27.9
Cr_2O_3	0.39	0.29	0.47	0.05	0.16	0.15	0.04	0.26	0.09	0.05
FeO	10.74	12.66	13.86	1.55	4.90	6.16	3.56	4.42	5.70	6.25
MnO	0.19	0.21	0.20	0.02	0.05	0.09	0.07	0.08	0.07	0.05
MgO	8.15	8.40	7.40	1.71	7.79	7.83	2.23	4.47	5.44	6.12
CaO	12.54	11.69	12.20	18.72	14.61	13.74	17.11	16.18	15.17	15.19
Na_2O	0.49	0.43	0.50	0.18	0.37	0.30	0.36	0.34	0.36	0.30
K_2O	0.03	0.03	0.05	0.01	n.d.	0.03	0.01	0.04	0.04	0.03
P_2O_5	0.04	0.03	0.08	0.02	n.d.	0.03	0.03	0.02	0.09	0.09
Sum	98.7	98.3	99.0	97.5	97.9	97.9	98.1	97.5	98.8	100.0
Mg′	0.57	0.54	0.49	0.66	0.74	0.69	0.53	0.64	0.63	0.64

Note A. The bulk analysis of MAC88105,41 is a normalized average of seven 10 μm EMP analyses of two separate fused beads. The Na_2O concentration is lower than that determined by INAA on 88105,41 powder (0.334%, Table 7), presumably as a result of volatilization during fusion.
Note B. Matrix analyses by broad beam EMP; beam diameter = 30-50 μm.
Note C. MAC88105,35 C1 matrix analysis by broad beam (BB) and bulk analysis (normalized) by fused bead (FB).
Note D. See Figure 2e, backscattered-electron image of this clast.
Note E. See Figure 2g, backscattered-electron image.
Note F. See Figure 2f, backscattered-electron image.
Note G. See Figure 2c, transmitted light photomicrograph.
Mg′ = molar Mg/(Mg+Fe); (n) = number of analyses; n.d. = not determined.

The first three clasts discussed below are relatively mafic compared to Apollo 16 samples and appear to be relict igneous rocks. They are similar to several clasts found in Y791197, ALHA81005, and Y82192 (RYDER and OSTERTAG, 1983; TREIMAN and DRAKE, 1983; GOODRICH et al., 1984; TAKEDA et al., 1987; GOODRICH and KEIL, 1987). All three plot within the ferroan anorthosite field of lunar plutonic rocks in Fig. 5.

Troctolitic anorthosite clast W2 (INAA subsamples W2A through W2F)

Thin section MAC88105,97 is small and contains the edge of clast W2 and some of the adjoining breccia matrix (Fig. 9). The area of monomict material constitutes a 1 mm by 3 mm portion of the thin section. The optically determined mode (converted to mass fraction) of this portion of the clast is 59% anorthite (maskelynitized), 36% olivine, 4.5% pyroxene (mostly augite with rare orthopyroxene intergrowths), and trace amounts of ilmenite and chromite. Thus, the thin section indicates that clast W2 is an anorthositic troctolite (based on volume fractions and the recommended classification of STÖFFLER et al., 1980). However, the material analyzed by INAA consists of six subsamples of the clast that differ substantially from each other in composition because of the coarse grain size of the clast and the small size of the subsamples (Table 7, subsamples W2A-W2F). Based on the mass-weighted mean composition of the subsamples (Table 7) and on mineral compositions by EMP analysis (Tables 4–6), we estimate that the portion of the clast analyzed by INAA

Table 4. Average plagioclase analyses in samples from MAC88105.

TS: (n):	Tr anor (,97 W2) (8)	Gab nor (,97) (4)	Anor nor (,80) (4)	Gran bx (,35 C1) (2)	Bas clst (,80) (2)	Mineral clasts (8)
SiO_2	43.79	44.55	44.24	45.40	45.45	43.52
Al_2O_3	35.66	35.72	35.83	34.39	33.77	35.18
FeO	0.30	0.38	0.18	0.33	0.33	0.17
MgO	0.07	0.02	0.05	0.15	0.16	0.08
CaO	18.96	18.62	19.15	19.03	19.26	18.92
Na_2O	0.32	0.45	0.31	0.41	0.42	0.31
K_2O	0.02	0.02	0.01	0.05	0.02	0.01
Sum	99.1	99.8	99.8	99.7	99.4	98.2
Cations						
Si IV	2.042	2.060	2.047	2.101	2.112	2.047
Al IV	1.959	1.946	1.954	1.875	1.849	1.951
Sum T site	4.001	4.006	4.001	3.976	3.961	3.998
Fe^{2+}	0.012	0.015	0.007	0.013	0.013	0.007
Mg	0.005	0.002	0.004	0.010	0.011	0.006
Ca	0.947	0.923	0.950	0.943	0.959	0.953
Na	0.029	0.041	0.028	0.036	0.038	0.028
K	0.001	0.001	<0.001	0.003	0.001	<0.001
Sum others	0.993	0.981	0.989	1.005	1.021	0.994
An	96.9	95.6	97.1	96.0	96.1	97.1
Ab	3.0	4.2	2.9	3.7	3.8	2.9
Or	0.11	0.15	0.04	0.29	0.10	0.05

Barium was analyzed but not detected at significant concentrations.
TS = Thin section number and clast designation.
(n) = number of analyses.

(MAC88105,51) contains 79 wt% anorthite, 15% olivine, and 6% augite, plus minor low-Ca pyroxene and chromite. Thus, the 32 mg of material in our bulk sample is troctolitic anorthosite in composition. The effect of the variation in the modal proportions of anorthite and augite among the small subsamples is strikingly evident in the chondrite-normalized REE patterns (Fig. 12).

Clast W2 is strongly shocked, and its original texture is obscured by partial maskelynitization of anorthite and pervasive fracturing of all minerals to a degree exceeding that of the adjoining breccia matrix (Fig. 11). Individual olivine grains are anhedral and range in size from 50 to 500 μm. Pyroxene grains range in size from 30 to 150 μm. Areas of monomineralic plagioclase span up to 600 μm. Minerals of this clast are unzoned and have uniform compositions. Plagioclase compositions are in the range $An_{96.4-97.4}$ (Table 4). Mafic silicate compositions are olivine: Fo_{55}, clinopyroxene: $Wo_{39}En_{43}Fs_{18}$, and low-Ca pyroxene: $Wo_4En_{60}Fs_{36}$ (Tables 5 and 6). The uniform mineral compositions indicate that this clast is monomict and of plutonic origin. Concentrations of Ir and Au in all six subsamples analyzed by INAA are below detection limits (<1 ng/g each for the largest subsample); the mean Ni concentration is 29 μg/g, which is consistent with negligible extralunar meteorite contamination for such an olivine-rich rock. The mineral compositions are similar to those of a troctolitic anorthosite clast found in Y82192

Table 5. Representative pyroxene analyses in samples from MAC88105.

TS:	Troct anorthosite (88105,97 W2)		Gabbronorite (88105,97)		Anorth norite (88105,80)		Gran bx (,35 C1)	Gran bx (,80)	Basaltic clast (88105,80)	
	Hyp	Aug	Hyp	Aug	Hyp	Aug			zoned Pig	Aug
SiO_2	52.35	51.57	51.28	51.85	51.38	51.12	52.19	52.56	52.51	48.89
TiO_2	0.37	0.69	0.29	0.41	0.12	n.d.	1.13	0.50	0.97	2.28
Al_2O_3	0.62	1.40	0.60	0.84	0.64	0.97	1.68	0.70	3.73	4.00
Cr_2O_3	0.18	0.35	0.16	0.26	0.37	n.d.	0.57	0.25	0.44	0.04
FeO	22.62	11.16	28.14	12.45	24.37	12.30	13.49	22.35	14.14	15.14
MnO	0.38	0.22	0.47	0.22	0.43	n.d.	0.26	0.39	0.26	0.23
MgO	21.43	15.23	18.06	13.17	19.77	13.67	21.14	19.93	20.43	10.01
CaO	2.12	19.09	1.31	20.70	2.18	18.66	9.08	3.02	7.42	19.40
Na_2O	<0.01	0.02	0.01	0.03	0.01	0.05	0.03	<0.01	0.02	0.14
Sum	100.1	99.7	100.3	99.9	99.3	96.8	99.6	99.7	99.9	100.1
Cations										
Si IV	1.963	1.937	1.966	1.962	1.963	1.983	1.927	1.979	1.920	1.868
Al IV	0.027	0.060	0.027	0.037	0.029	0.017	0.073	0.021	0.080	0.132
T site	1.990	1.997	1.993	2.000	1.991	2.000	2.000	2.000	2.000	2.000
Al VI	0.000	0.002	0.000	0.000	0.000	0.028	0.000	0.010	0.081	0.048
Ti	0.011	0.019	0.008	0.012	0.004	0.000	0.031	0.014	0.027	0.066
Cr	0.005	0.010	0.005	0.008	0.011	0.000	0.017	0.007	0.013	0.001
Fe^{2+}	0.709	0.350	0.902	0.394	0.778	0.399	0.417	0.704	0.432	0.484
Mn	0.012	0.007	0.015	0.007	0.014	0.000	0.008	0.012	0.008	0.007
Mg	1.198	0.853	1.032	0.743	1.126	0.791	1.164	1.119	1.114	0.570
Ca	0.085	0.768	0.054	0.839	0.089	0.776	0.359	0.122	0.291	0.794
Na	0.000	0.002	0.000	0.002	0.001	0.004	0.002	0.000	0.001	0.011
M1,M2	2.020	2.012	2.017	2.005	2.023	1.997	1.998	1.988	1.967	1.981
Mg'	0.63	0.71	0.53	0.65	0.59	0.66	0.74	0.61	0.72	0.54
Wo	4.3	39.0	2.7	42.5	4.5	39.5	18.5	6.3	15.8	43.0
Fs	35.6	17.8	45.4	19.9	39.1	20.3	21.5	36.2	23.5	26.2
En	60.1	43.2	51.9	37.6	56.5	40.2	60.0	57.5	60.6	30.9

TS = Thin section number and clast designation; Mg' = molar Mg/(Fe+Mg); n.d. = not determined.

Table 6. Average and representative olivine analyses in samples from MAC88105.

TS:	Tr anor (,97 W2)	Gab nor (,97)	Anor nor (,80)	Gran bx (,35 C1)	Bas clst (,80)
(n):	(7)	(2)	(1)	(2)	(1)
Note:	A				
SiO_2	35.31	33.60	34.79	38.01	32.60
TiO_2	0.03	0.05	0.03	0.09	0.31
Al_2O_3	0.01	0.15	0.01	0.48	0.13
Cr_2O_3	0.02	<0.01	<0.01	0.13	0.01
FeO	37.95	48.09	39.83	26.43	55.14
MnO	0.40	0.48	0.37	0.24	0.52
MgO	26.05	17.95	24.55	34.60	9.68
CaO	0.14	0.19	0.06	0.32	0.66
Na_2O	<0.01	<0.01	<0.01	<0.01	<0.01
Sum	99.9	100.5	99.7	100.3	99.1
Cations					
Si IV	0.996	0.994	0.994	1.004	1.022
Al VI	0.000	0.005	0.000	0.015	0.005
Ti	0.001	0.001	0.001	0.002	0.007
Cr	<0.001	<0.001	<0.001	0.003	<0.001
Fe^{2+}	0.896	1.191	0.952	0.584	1.446
Mn	0.010	0.012	0.009	0.005	0.014
Mg	1.096	0.792	1.046	1.363	0.452
Ca	0.004	0.006	0.002	0.009	0.022
Na	<0.001	<0.001	<0.001	<0.001	<0.001
Sum oct.	2.007	2.007	2.010	1.981	1.946
Mg′	0.55	0.40	0.52	0.70	0.24
Ca	0.2	0.3	0.1	0.5	1.2
Fa	44.9	59.9	47.6	29.9	75.3
Fo	54.9	39.8	52.3	69.7	23.6

Note A. No compositional zoning observed. TS = Thin section number and clast designation; (n) = number of analyses; Mg′ = molar Mg/(Fe+Mg).

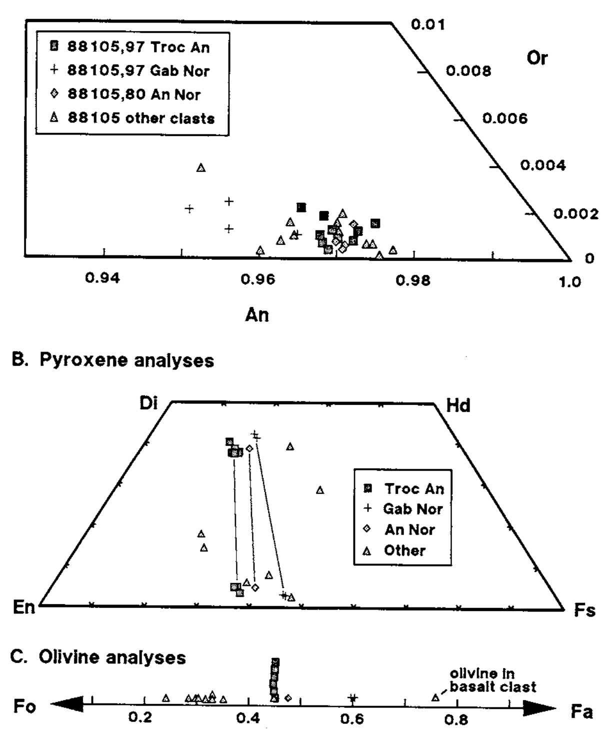

FIG. 4. Major mineral compositions in clasts from MAC88105. Pyroxene tielines join analyses from the same clast. Troc An—troctolitic anorthosite; Gab Nor—gabbronorite; An Nor—anorthositic norite; Other—probably polymict.

(GOODRICH and KEIL, 1987; TAKEDA et al., 1987) and a ferroan igneous lithology in Y791197 (GOODRICH and KEIL, 1987). A ferroan troctolitic anorthosite clast has also been described from Apollo 16 breccia 64435 (JAMES et al., 1989), but its mafic minerals have substantially higher values of Mg′.

Gabbronorite

A gabbronorite clast about 300 by 400 μm in dimension also occurs in thin section MAC88105,97. It consists of 52 vol% plagioclase, 34% low-Ca pyroxene, 8% augite, 5% olivine, and 1% ilmenite. Several augite crystals contain thin exsolution lamellae of orthopyroxene. Pyroxene grains range up to 100 μm in size, and olivine up to 50 μm. Plagioclase composition is An_{95-96}, olivine: Fo_{40}, orthopyroxene: $Wo_3En_{52}Fs_{45}$, and augite: $Wo_{42}En_{38}Fs_{20}$ (Fig. 4). This clast is only moderately shocked, and some of the plagioclase is crystalline. Although the minerals are not coarse grained, the uniformity of mineral compositions and pyroxene exsolution suggest a plutonic origin. This clast is very similar to a ferroan gabbronorite clast, ALHA81005,48-2A (GOODRICH et al., 1984), in both mode and mineral composition.

Anorthositic norite

An anorthositic norite clast occurs in thin section MAC88105,80, which is about 600 by 600 μm in size. It consists of 69% plagioclase, 25% low-Ca pyroxene, 2.5% augite, and 3% olivine, plus traces of ilmenite. Plagioclase grains range up to 300 μm in size, hypersthene: 200 μm, and olivine: 100 μm. EMP analyses indicate plagioclase of An_{97}, olivine:

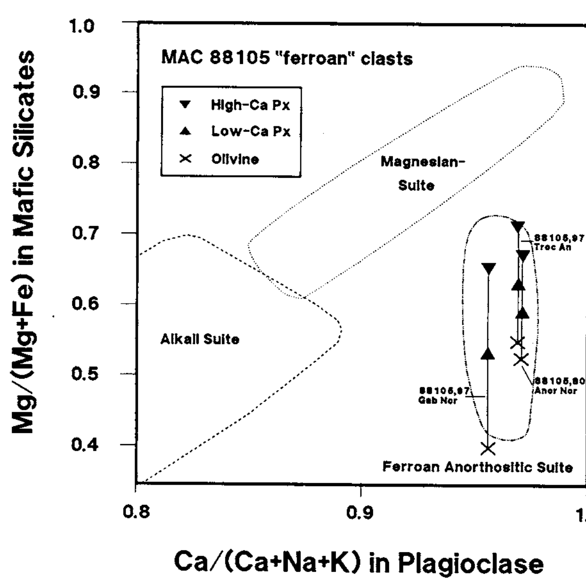

FIG. 5. Molar Mg/(Mg + Fe) in mafic minerals vs. An content of plagioclase for monomict clasts in MAC88105,97 and ,80.

Table 7. INAA results for samples from MAC88104 and MAC88105.

Sample number		mass mg	Na_2O %	CaO %	Sc µg/g	Cr µg/g	FeO %	Co µg/g	Ni µg/g	Sr µg/g	Zr µg/g	Cs µg/g	Ba µg/g
Matrix-rich chips													
MAC88105,35	M01	6.924	0.356	16.8	7.92	557	4.10	13.37	139	142	46	0.05	28
MAC88105,35	M02	4.967	0.356	16.6	8.42	633	4.39	15.35	143	149	41	0.05	32
MAC88105,35	M03	4.679	0.349	16.5	8.36	607	4.32	15.65	149	142	33	0.02	32
MAC88105,35	M04	4.807	0.335	16.6	7.89	599	4.15	12.74	122	157	39	0.02	27
MAC88105,35	M05	5.992	0.361	16.7	8.99	654	4.54	14.89	135	148	32	0.03	26
MAC88105,35	M06	5.976	0.340	16.5	8.07	587	4.20	14.72	141	159	29	0.03	33
MAC88105,35	M07	3.589	0.357	16.4	8.58	645	4.38	16.45	176	156	44	0.02	35
MAC88105,35	M08	6.971	0.333	16.4	8.89	824	4.58	14.52	136	149	29	0.04	32
MAC88105,35	M09	5.566	0.337	16.4	8.43	592	4.55	17.78	209	143	28	0.03	29
MAC88105,35	M10	10.493	0.334	16.0	8.04	575	4.35	16.01	176	143	26	<0.2	32
MAC88105,35	M11	4.749	0.334	16.6	7.81	552	4.08	13.37	137	157	62	0.04	38
MAC88105,35	M12	8.187	0.339	16.4	8.46	645	4.35	13.88	131	151	59	0.03	34
MAC88105,35	M13	7.252	0.339	16.6	8.68	653	4.42	16.52	203	143	44	0.03	36
MAC88104,15	M14	11.388	0.341	16.5	8.64	631	4.31	13.54	124	150	37	0.03	30
MAC88104,15	M15	6.882	0.337	16.5	8.24	625	4.27	14.43	146	149	33	0.03	32
MAC88104,15	M16	5.655	0.340	16.5	9.76	665	4.63	13.38	123	142	31	0.03	32
MAC88104,15	M17	5.833	0.322	16.7	8.01	581	4.09	13.90	136	148	35	0.03	30
uncertainty[a]			0.003	0.4	0.08	6	0.04	0.15	10	10	9	0.01	3
Clasts													
MAC88105,35	C1A	3.426	0.345	14.7	7.45	564	6.08	35.4	527	151	43	<0.06	34
MAC88105,35	C1B	0.854	0.347	14.6	5.86	460	5.75	33.3	471	146	36	<0.2	38
wt'd. mean	C1	4.280	0.345	14.7	7.13	543	6.01	35.0	515	150	41	<0.1	35
MAC88105,51	W2A	4.634	0.229	14.2	6.60	1554	10.95	25.9	37	117	23	<0.05	12
MAC88105,51	W2B	1.872	0.244	15.8	12.48	873	8.05	18.4	25	134	17	<0.07	11
MAC88105,51	W2C	1.229	0.314	17.8	5.64	433	2.71	6.39	23	146	26	<0.08	12
MAC88105,51	W2D	4.670	0.287	18.3	12.91	676	3.82	9.26	24	133	18	<0.07	16
MAC88105,51	W2E	1.456	0.307	18.7	8.70	407	2.20	4.41	10	147	21	<0.06	14
MAC88105,51	W2F	18.308	0.263	16.3	7.90	670	7.28	17.2	30	122	12	<0.05	12
wt'd. mean	W2	32.169	0.264	16.4	8.66	789	6.95	16.4	29	126	16	<0.05	13
MAC88104,15	C3	1.426	0.292	17.9	3.73	196	1.34	4.81	74	160	2	<0.04	8
MAC88104,15	C4	9.173	0.287	16.0	10.07	582	5.31	11.48	48	150	31	0.04	20
MAC88104,15	C5	9.047	0.279	16.0	10.69	571	5.33	11.70	53	134	34	0.04	17
MAC88104,15	C6	4.039	0.324	16.6	8.69	614	4.55	13.35	121	145	20	0.06	28
Weighted means (matrix-rich, Mxx)													
MAC88104,15	n=4	29.758	0.336	16.5	8.64	626	4.32	13.8	131	147	34	0.04	30
MAC88105,35	n=13	80.152	0.343	16.5	8.35	625	4.35	15.0	154	148	38	0.03	31
MAC88104&5	n=17	109.91	0.341	16.5	8.43	626	4.34	14.7	148	148	37	0.04	31
Powder mean													
MAC88105,41	n=4	193.03	0.334	16.8	8.47	638	4.35	14.51	150	156	34	0.040	31
Powder[b]													
MAC88105 P1		48.03	0.335	17.0	8.50	637	4.36	14.36	151	163	33	0.043	30
MAC88105 P2		48.33	0.331	16.5	8.44	649	4.33	14.50	158	160	39	0.032	37
MAC88105 P3		47.42	0.335	16.9	8.48	633	4.37	14.53	146	153	37	0.052	33
MAC88105 P4		49.25	0.335	16.7	8.46	633	4.35	14.66	146	151	29	0.032	25
mean		193.03	0.334	16.8	8.47	638	4.35	14.51	150	156	34	0.040	31
stnd. dev.			0.002	0.2	0.03	7	0.02	0.12	5	5	4	0.010	5
% stnd. dev.			0.60	1.32	0.30	1.19	0.39	0.85	3.78	3.62	12.8	24.	16.
matrix/powder[c]			1.021	0.98	0.995	0.981	0.997	1.012	0.99	0.95	1.09	1.	1.01

Fo_{52}, orthopyroxene: $Wo_4En_{57}Fs_{39}$, and augite: $Wo_{40}En_{40}Fs_{20}$ (Fig. 4).

Ir-rich clast C1

Clast C1 is a poikiloblastic granulitic breccia composed of 5–10 µm olivine granules (Fo_{70}), pyroxene poikiloblasts ($En_{60}Fs_{21}Wo_{19}$) up to 400 µm in size, and matrix plagioclase, including very fine-grained granular-recrystallized patches up to 300 µm in diameter. The breccia is clast-bearing (10–15%, visual estimate) and the clasts consist mainly of plagioclase (An_{95-97}), up to several hundred micrometers in size. The clast contains minor ilmenite (10–100 µm irregular masses) and grains of Fe-Ni-Co metal up to 40 µm in diameter. The metal composition is 93.2% Fe, 6.3% Ni, and 0.49% Co (mean of two grains with nearly identical compositions). Macroscopically, the clast has a tan hue resulting from brown alteration halos surrounding metal and some ilmenite grains. The major-element composition of the granulitic matrix is given in Table 3; concentrations of Fe, Ca, Na, and Cr are similar to those determined by INAA for bulk fragments of this clast (Table 7). The bulk composition of the matrix is similar to those of granulitic breccias in MAC88105,80 (Table 3).

Clast C1 has lithophile element concentrations similar to those of the bulk meteorite, although it has slightly lower concentrations of Sc, Cr, and Ca (Fig. 9, Table 7). The most distinctive feature of clast C1, however, is its high concentrations of siderophile elements (Ni: 515 µg/g, Co: 35 µg/g, Au: 6.4 ng/g, and Ir: 34 ng/g). These elements are undoubt-

Table 7. (Continued) INAA results for samples from MAC88104 and MAC88105.

Sample number	La µg/g	Ce µg/g	Sm µg/g	Eu µg/g	Tb µg/g	Yb µg/g	Lu µg/g	Hf µg/g	Ta µg/g	Ir ng/g	Au ng/g	Th µg/g	U µg/g
Matrix-rich chips													
MAC88105 M01	2.16	5.43	1.044	0.782	0.216	0.857	0.120	0.81	0.086	5.5	1.6	0.37	0.09
MAC88105 M02	2.56	6.58	1.210	0.780	0.257	1.028	0.146	0.93	0.106	5.3	1.8	0.43	0.12
MAC88105 M03	2.38	5.91	1.095	0.780	0.239	0.948	0.131	0.88	0.105	6.2	2.7	0.38	0.10
MAC88105 M04	2.20	5.85	1.050	0.775	0.216	0.897	0.123	0.83	0.106	4.7	1.8	0.37	0.09
MAC88105 M05	2.26	5.93	1.111	0.766	0.227	0.941	0.128	0.84	0.090	5.9	1.4	0.35	0.09
MAC88105 M06	2.31	5.92	1.099	0.790	0.242	0.939	0.129	0.84	0.109	6.1	2.0	0.38	0.10
MAC88105 M07	2.59	6.51	1.213	0.796	0.257	0.995	0.141	0.92	0.107	7.2	2.4	0.41	0.10
MAC88105 M08	2.20	5.76	1.073	0.769	0.219	0.910	0.125	0.87	0.106	6.5	1.4	0.36	0.09
MAC88105 M09	2.33	6.40	1.158	0.787	0.238	0.971	0.133	0.90	0.112	10.2[d]	2.1	0.40	0.10
MAC88105 M10	2.26	6.04	1.110	0.762	0.234	0.906	0.130	0.83	0.125	27.3[d]	1.7	0.41	0.10
MAC88105 M11	2.28	6.15	1.128	0.788	0.230	0.948	0.131	1.17	0.100	5.3	1.1	0.38	0.11
MAC88105 M12	2.81	7.24	1.310	0.773	0.268	1.026	0.144	0.96	0.133	5.9	2.1	0.42	0.14
MAC88105 M13	2.71	6.80	1.241	0.792	0.259	1.036	0.141	0.93	0.119	7.7	2.3	0.43	0.11
MAC88104 M14	2.38	5.95	1.108	0.782	0.231	0.952	0.131	0.90	0.109	6.7	1.2	0.40	0.12
MAC88104 M15	2.52	6.47	1.201	0.770	0.251	1.035	0.140	0.91	0.107	5.5	2.0	0.41	0.12
MAC88104 M16	2.13	5.94	1.066	0.773	0.229	0.896	0.126	0.81	0.090	7.2	1.9	0.34	0.14
MAC88104 M17	2.13	5.32	0.979	0.760	0.215	0.842	0.121	0.76	0.101	4.9	1.3	0.37	0.09
uncertainty[a]	0.03	0.14	0.016	0.014	0.008	0.016	0.003	0.02	0.009	0.6	0.5	0.02	0.02
Clasts													
MAC88105 C1A	2.50	7.04	1.287	0.801	0.264	1.027	0.146	1.03	0.169	33.0	6.4	0.47	0.15
MAC88105 C1B	2.57	7.14	1.223	0.804	0.229	0.868	0.124	0.90	0.140	39.6	6.3	0.47	0.16
mean C1	2.51	4.1	1.274	0.802	0.257	0.995	0.142	1.01	0.163	34.3	6.4	0.47	0.15
MAC88105 W2A	0.69	1.85	0.351	0.542	0.078	0.356	0.056	0.19	<0.04	<2	<2	0.07	<0.1
MAC88105 W2B	0.80	2.42	0.750	0.572	0.195	0.685	0.094	0.54	<0.05	<2	<2	0.07	<0.5
MAC88105 W2C	0.89	2.26	0.496	0.713	0.102	0.340	0.043	0.27	<0.07	<3	<2	0.06	<0.2
MAC88105 W2D	0.92	2.64	0.848	0.666	0.214	0.714	0.089	0.47	<0.04	<2	<2	0.09	<0.3
MAC88105 W2E	0.92	2.39	0.617	0.700	0.146	0.493	0.065	0.39	<0.05	<3	<2	0.09	<0.2
MAC88105 W2F	0.75	2.14	0.484	0.607	0.114	0.427	0.059	0.25	<0.02	<1	<1	0.066	<0.05
mean W2	0.779	2.20	0.540	0.612	0.129	0.473	0.065	0.29	<0.02	<1	<1	0.07	<0.1
MAC88104 C3	0.64	1.24	0.302	0.759	0.062	0.276	0.039	0.17	0.010	<2	<2	0.05	0.05
MAC88104 C4	1.24	3.76	0.693	0.726	0.150	0.666	0.095	0.51	0.061	3.1	0.7	0.19	0.03
MAC88104 C5	1.23	3.61	0.706	0.711	0.154	0.675	0.102	0.56	0.064	5.1	<2	0.15	0.04
MAC88104 C6	1.90	4.68	0.904	0.751	0.192	0.825	0.115	0.67	0.085	3.9	0.9	0.33	0.09
Weighted means (matrix-rich, Mxx)													
MAC88104,15	2.32	5.94	1.096	0.773	0.232	0.939	0.130	0.86	0.103	6.2	1.5	0.39	0.12
MAC88105,35	2.39	6.20	1.143	0.778	0.239	0.952	0.132	0.89	0.110	9.1[d]	1.9	0.39	0.10
MAC88104&5	2.37	6.13	1.131	0.777	0.237	0.948	0.132	0.88	0.108	8.3[d]	1.8	0.39	0.11
Powder mean													
MAC88105,41	2.48	6.38	1.203	0.790	0.251	0.987	0.138	0.90	0.112	7.7	2.7	0.42	0.10
Powder[b]													
MAC88105 P1	2.49	6.34	1.195	0.795	0.255	0.987	0.139	0.88	0.115	6.6	2.2	0.42	0.08
MAC88105 P2	2.46	6.39	1.202	0.786	0.246	0.976	0.138	0.92	0.114	7.3	2.6	0.38	0.12
MAC88105 P3	2.47	6.37	1.209	0.794	0.256	0.989	0.139	0.90	0.110	6.0	2.9	0.41	0.11
MAC88105 P4	2.50	6.41	1.205	0.783	0.245	0.996	0.135	0.90	0.108	10.7	3.1	0.49	0.10
mean	2.48	6.38	1.203	0.790	0.251	0.987	0.138	0.90	0.112	7.7	2.7	0.42	0.10
stnd. dev.	0.02	0.03	0.006	0.006	0.006	0.008	0.002	0.02	0.003	2.1	0.4	0.05	0.02
% stnd. dev.	0.74	0.47	0.49	0.75	2.32	0.84	1.37	1.91	2.96	28.	14.	11.4	20.
matrix/powder[c]	0.955	0.962	0.940	0.984	0.946	0.961	0.957	0.98	0.97	1.09	0.65	0.92	1.05

a One-standard-deviation estimate of analytical uncertainty.
b Also, As: <0.2 µg/g; Br: 0.10 ± 0.04 µg/g; Rb: <5 µg/g; Sb: <0.3 µg/g; Nd: 4.2 ± 0.5 µg/g; W: <0.3 µg/g.
c Ratio of weighted mean of seventeen matrix-rich chips of MAC88104&5 (110 mg) to mean of four 88105,41 powder samples (193 mg).
d Contains a portion of the Ir-rich clast C1.

edly carried by the Fe-Ni metal grains observed in the thin section. Although siderophile-element-bearing metal derived from meteorites striking the Moon is common in the polymict Apollo samples, clast C1 and, presumably, the metal it contains are unusual in containing a high concentration of Ir compared to Ni and Au, which leads to low ratios of Au/Ir and Ni/Ir, about two-thirds the chondritic ratios (the Au/Ni ratio is chondritic). Although similarly low Au/Ir ratios are observed in some Apollo lunar samples, they have not been observed in Apollo samples so strongly contaminated by extralunar debris (Fig. 10). Thus, clast C1 is unusual in having both a low Au/Ir ratio and high absolute concentrations of siderophile elements. Other high-Ir, low-Au/Ir clasts have been observed in MAC88104/5 (LINDSTROM et al., 1991; KOEBERL et al., 1991).

Other clasts

Clast C3, which has the lowest concentrations of ITEs, is a cataclastic, crystalline anorthosite with relict plagioclase crystals up to 700 µm in grain size. Based on the INAA results for Na and Ca (Table 7), the clast is ~91 wt% plagioclase (~93 vol%) and the average composition of the plagioclase is $An_{97.1}$. Concentrations of compatible trace elements (Na,

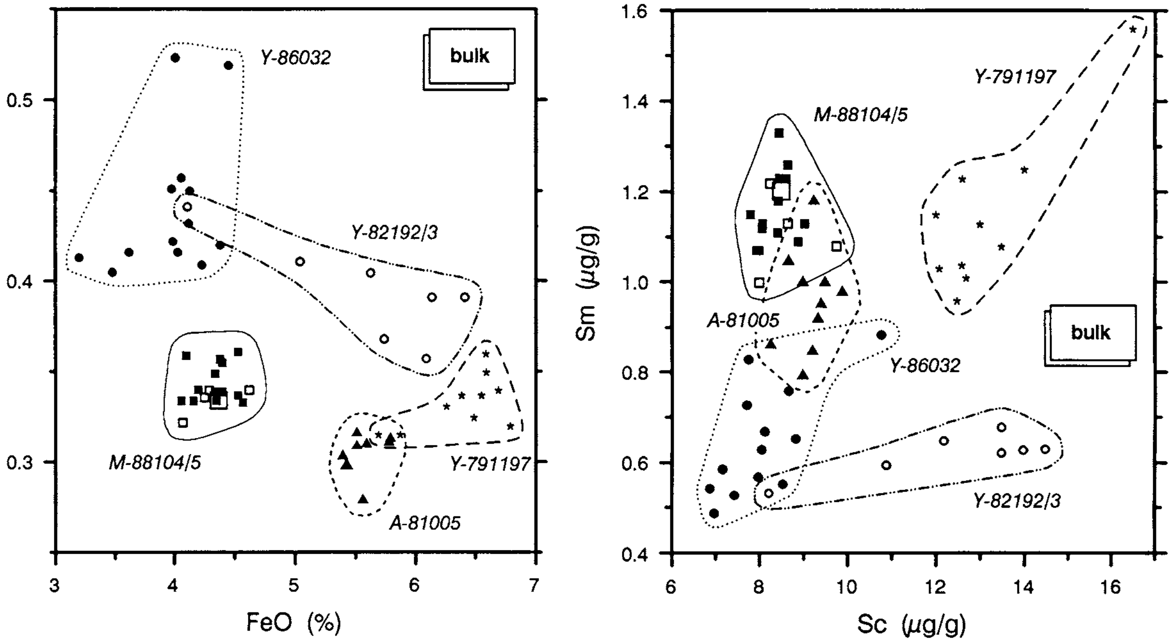

FIG. 6. Comparison of Na, Fe, Sm, and Sc concentrations in matrix-rich (i.e., clast-poor) or bulk samples of nonmare lunar meteorites. For M-88104/5, the filled squares are for chips of MAC88105 and the small open squares are for chips of MAC88104; the large open square is the mean of the powdered samples (MAC88105,41). Data are from the following sources: ALHA-81005—BOYNTON and HILL (1983), KALLEMEYN and WARREN (1983), KOROTEV et al. (1983), LAUL et al. (1983), and PALME et al. (1983); Y-791197—FUKUOKA et al. (1986b), KOEBERL (1988), LINDSTROM et al. (1986), OSTERTAG et al. (1986), and WARREN and KALLEMEYN (1986); Y-82192/3—BISCHOFF et al. (1987), FUKUOKA et al. (1986a), KOEBERL (1988), LINDSTROM et al. (1987), and WARREN and KALLEMEYN (1987); Y-86032—unpubl. data, this lab; MAC88104/5—this work.

Ca, Fe, Cr, Co, Sr, and Eu) are very similar to those of some ferroan anorthosites from Apollo 16, e.g., 62237,26B and 67075,37A of HASKIN et al. (1981); however, ITE concentrations are about a factor of 2 to 4 greater in clast C3. The Ni concentration of 74 μg/g indicates that the sample is probably contaminated by meteoritic debris.

Clast subsamples C4 and C5, which are nearly identical in composition (Fig. 9), are two fragments of a single clast. The clast is a fragmental breccia, possibly composed of a single precursor rock type such as anorthositic gabbro. There are several medium-grained patches of plagioclase (500 μm crystals) and pyroxene (300 μm). One of the fragments contains some glassy material along its edges and also contains some disseminated opaque grains. Concentrations of Sc are greater than for the bulk meteorite, presumably because of a higher proportion of clinopyroxene. ITE concentrations are about half those of the bulk meteorite.

Clast C6 is the most similar to the bulk meteorite in composition. It is a clast-rich impact melt breccia that has a partly glassy (finely devitrified) matrix. This clast is petrographically similar to the most abundant melt breccia clasts in thin section MAC88105,80.

Cerium anomalies

Several of the clast samples have Ce concentrations that are anomalous when compared to those of La and Sm (Figs. 12 and 13). Both negative (clast C3) and positive (C1, C4, and C5) Ce anomalies occur. No anomalies, or only small anomalies, occur in other clasts (W2 and C6) and the matrix-rich chips. Although small positive anomalies in Ce abundances have been previously reported in some lunar samples by mass-spectrometric isotope dilution (MASUDA et al., 1972, 1974), this is the first time in over 1000 analyses of lunar samples in this laboratory that we have seen in our own data apparent enrichments or depletions of Ce relative to other light REEs that we believe to be outside the range of any possible analytical error.

We suspect that these anomalies are not the result of some fractionation process that occurred on the Moon, but are caused by terrestrial weathering. Both positive and negative Ce anomalies, believed to have been caused by terrestrial weathering, have been reported in both bulk samples and minerals from Antarctic eucrites (MITTLEFEHLDT and LINDSTROM, 1991; HEAVILON and CROZAZ, 1990; FLOSS and CROZAZ, 1990). MITTLEFEHLDT and LINDSTROM (1991) suggest that (1) melt water, acidified by equilibration with the atmosphere, dissolves REE-bearing phosphate minerals in the eucrites and oxidizes Ce^{3+} to Ce^{4+}, (2) the trivalent REEs are mobilized more readily than Ce^{4+} in solution, and (3) positive anomalies result from net loss of trivalent REEs and negative anomalies result from net gain. HEAVILON and CROZAZ (1990) and FLOSS and CROZAZ (1990) report both positive and negative anomalies, as well as no anomalies, in different regions of a single pyroxene grain, although positive anomalies were more common. Anomalies in plagioclase were rare and always negative. Although these anomalies were of much greater relative magnitude ($0.31 < Ce/Ce^* < 30$; see Fig. 13 caption) than those observed here, our results are in qualitative agreement. The pyroxene-rich samples (clasts C4 and C5) have the largest positive Ce anomalies while the plagioclase-rich sample (clast C3) has a negative anomaly. If terrestrial weathering processes cause Ce anomalies in Antarctic eucrites, then they are also likely to affect other Antarctic achondrites, although Ce anomalies have not been previously reported in other lunar meteorites.

The observations that (1) no anomalies occur in the powdered sample, which was prepared from 20 g of MAC88105 and (2) Ce anomalies are more evident in our data than in the data of others who analyzed larger subsamples together indicate that there was no

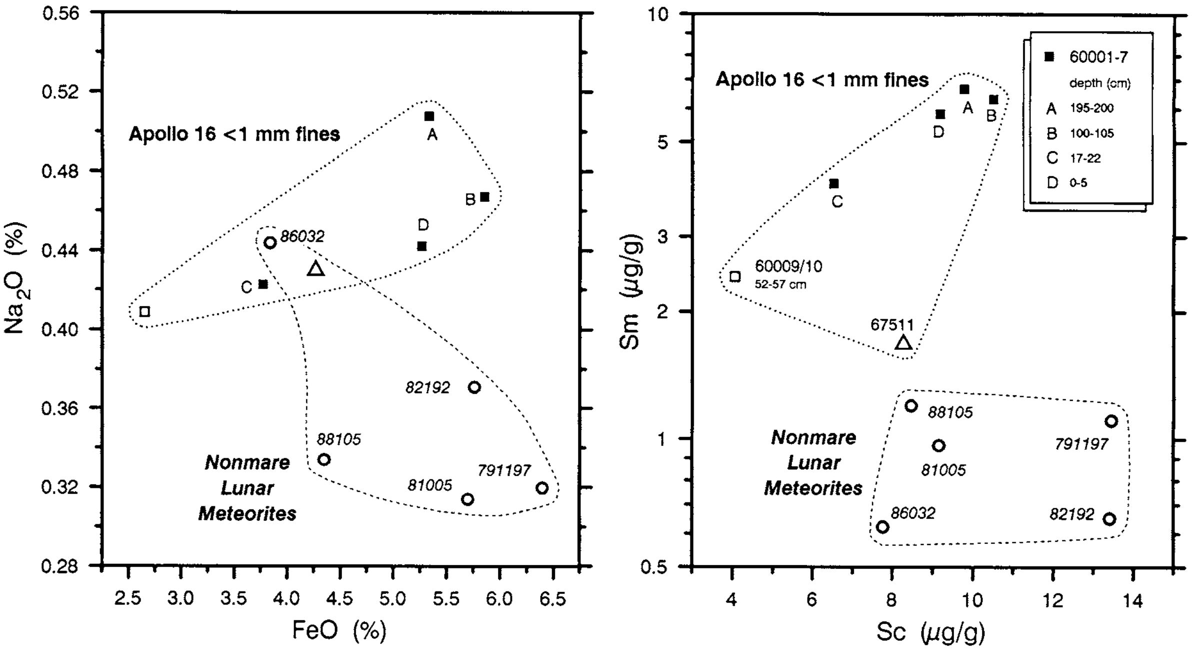

FIG. 7. Comparison of bulk samples of nonmare lunar meteorites with <1 mm fines from Apollo 16. The logarithmic Sm axis shows that Sm concentrations in representative samples of <1 mm fines from Apollo 16 soils span a factor of 4, whereas average Sm concentrations in bulk samples of nonmare lunar meteorites span only a factor of 2. Squares are for core samples and in each case represent the mean of 10 stratigraphically consecutive samples (0.5 cm sampling interval) in the 5 cm–wide depth range indicated in the legend. Designations A, B, C, and D for the 60001-7 samples signify that the samples are from units of the same designation identified on the basis of petrographic differences ("modal petrography units") by VANIMAN et al. (1976). The soil between 52 and 57 cm depth in 60009/10 is the most feldspathic of the Apollo 16 soils. North Ray Crater soil 67511 has the lowest concentrations of ITEs among Apollo 16 fines, only 40% greater than for MAC88104/5. (The very immature fines sample, 67711, with 1.3 µg/g Sm is even lower, but with 0.72% Na_2O, this is a very unusual sample; it was apparently derived entirely from a single boulder; KOROTEV, 1981.) Meteorite data are from the sources referenced in Fig. 6; Apollo 16 soil data are from KOROTEV (1991). The large range in Mg′ observed among the nonmare lunar meteorites is not observed in the LM-area core soils (MPU-B: Mg′ = 66; MPU-A: Mg′ = 68; NAVA et al., 1976). However, among the surface fines collected on the rim of North Ray Crater, values of Mg′ range from 0.63 (67511, 67461, 67481) to 0.71 (67941) (0.72, if 67711 is included). This is approximately the same range of Mg′ observed for the nonmare lunar meteorites (MAC88104/5: 0.62, this work, to ALHA81005: 0.73, WARREN et al., 1989).

net loss of trivalent REEs from the meteorite but that some process has redistributed trivalent REEs within the meteorite specimens over distances of up to several millimeters. The problem appears worse for Antarctic eucrites because even 100 mg samples have significant anomalies (MITTLEFEHLDT and LINDSTROM, 1991).

DISCUSSION

The MacAlpine Hills 88104 and 88105 meteorites are regolith breccias from the feldspathic crust of the Moon. They are compositionally indistinguishable and are undoubtedly paired specimens of a single meteorite. The low concentrations of Th and other ITEs compared to most polymict samples from the Apollo missions suggest that this meteorite, like the other nonmare lunar meteorites, was derived from a region of the Moon distant from nearside regions with Th concentrations (METZGER et al., 1977) as high as those at the Apollo landing sites (KOROTEV et al., 1983; KALLEMEYN and WARREN, 1983).

MAC88104/5 and the other lunar highland meteorites contain a suite of clasts composed of fragments of impact-derived breccias and igneous rocks. Even the fine-grained "matrix" of MAC88105 is rich in lithic clasts on a microscopic scale, and the lithic clasts are very finely crystalline- (or devitrified vitric-) matrix melt breccias. This has been observed in other lunar meteorites (e.g., Y82192; BISCHOFF et al., 1987), but the high modal abundance of lithic clasts in MAC88104/5 may set this meteorite apart from the other nonmare lunar meteorites and certainly distinguishes them from the highland breccia samples of the Apollo collection (cf. LINDSTROM et al., 1991; TAYLOR, 1991). MAC88104/5 represents the kind of regolith that we might expect to find as a blanket on a melt sheet (TAYLOR, 1991) or in the midst of several melt sheets. The very low proportion of glass fragments and the absence of agglutinates, however, indicate that this regolith received only minor surface exposure.

Petrographic and Petrologic Constraints on Crustal Precursors

In this section, we attempt to extrapolate from the clast assemblage and compositions of the meteorites to the nature (composition and distribution) of their igneous precursors. We consider three separate approaches in this exercise: (1) the igneous clasts may be unmodified samples of some of the

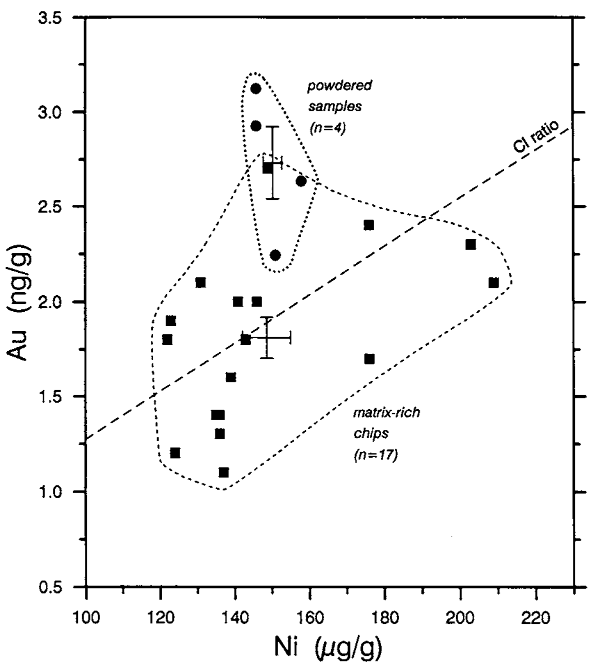

FIG. 8. Au and Ni concentrations in samples of matrix-rich chips from MAC88104/5 (squares) and subsamples of the powder MAC88105,41 (circles). The "error bars" represent the mean concentrations ± one sample standard deviation of the mean for the two sets of samples. The dashed line connects the origin with the point for CI chondrites. The difference in mean Au concentrations between the powdered samples and matrix-rich chips is significant at the 99% confidence interval (t-test).

precursor igneous rocks; (2) the individual mineral clasts may be a genetically related group; and (3) the polymict breccias and the meteorite matrix are mixtures of igneous materials, the compositions of which have been averaged by impact mixing. We explore these three approaches below.

Igneous clasts

The igneous clasts that occur in MAC88104/5 include apparent (because of their small size) samples of troctolitic anorthosite, anorthositic norite, anorthosite (*sensu stricto*), and gabbronorite (this work). Other reported clast types in MAC88104/5 include gabbroic anorthosite, troctolite, and basalt (NEAL et al., 1991); ferroan anorthosite and granulitic troctolitic anorthosite (WARREN and KALLEMEYN, 1991); anorthositic spinel-norite, norite, and anorthosite, all with generally ferroan mafic-mineral compositions (KOEBERL et al., 1991). Of those igneous clasts for which the mineral compositions are known, most have mineral compositions typical of ferroan-suite rocks, but are more mafic (e.g., norite, gabbronorite, anorthositic norite) than most ferroan-suite rocks in the Apollo collection. This has also been observed in other nonmare lunar meteorites. There is a dearth of "Mg-suite" igneous fragments among the lunar-highland meteorites, especially MAC88104/5. Values of Mg' for polymict lithic clasts and the bulk matrix of MAC88105 are also low, among the lowest of all the nonmare lunar meteorites. The limited ranges of mineral compositions and Mg' that we find in igneous clasts of MAC88105 suggest that the clasts may be petrogenetically related. Assuming that these clasts are not substantially more mafic than their parent rocks (i.e., they are representative samples), then the precursor igneous rocks were ferroan, but more mafic than the anorthosites typical of ferroan suite rocks from the Apollo missions, particularly Apollo 16.

Most ferroan-suite rocks are from Apollo 16, and most of these are anorthosites containing >95% plagioclase, although a few are more mafic (<90% plagioclase) (HASKIN et al., 1981; WARREN, 1990). WARREN (1990) calculates that the average concentration of plagioclase in ferroan-suite rocks is 93.7 ± 6.7 vol%, based on sixteen large rocks from Apollo 16 and one from Apollo 15. This contrasts with results for soils. The anorthositic component causing the principle compositional variation among samples of fines from two Apollo 16 cores is a ferroan anorthosite containing ~99% plagioclase (KOROTEV, 1991). This suggests that the large, mafic ferroan-suite rocks from Apollo 16 are atypical of their source.

The average or typical plagioclase content of the ferroan-suite rocks is an important parameter for constraining models of lunar crust formation. For us, there is as yet no satisfactory explanation for the high plagioclase concentration typical of samples of ferroan anorthosite in the Apollo collection. Such plagioclase-rich rocks would be an extreme product of crystallization of plagioclase plus, presumably, co-crystallized mafic minerals from any common igneous liquid. Examples of ferroan-suite rocks such as noritic anorthosite that might result from accumulation of plagioclase in a mafic liquid with incomplete separation of that liquid are at best rare among "pristine" rocks identified in the Apollo samples.

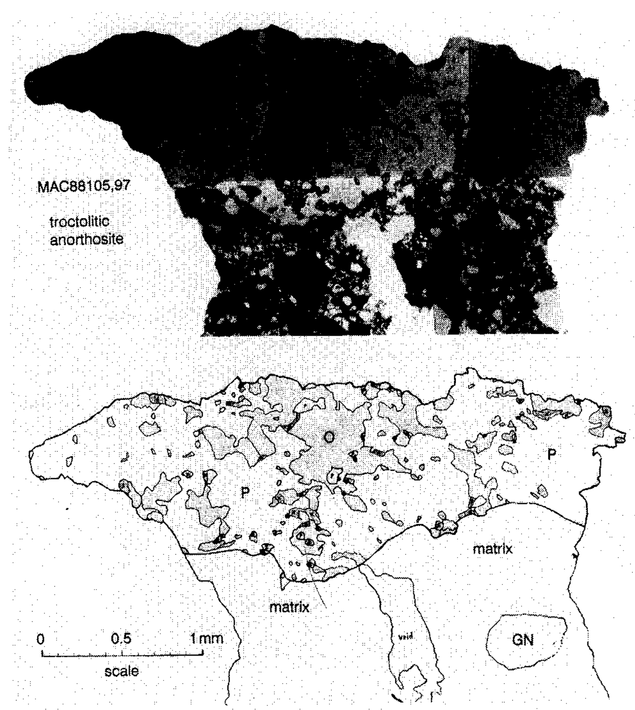

FIG. 9. Transmitted light photomosaic and sketch of troctolitic anorthosite clast W2, MAC88105,97. Mafic silicate is 90% olivine. P—plagioclase/maskelynite; X—pyroxene; O—olivine; I—ilmenite; C—chromite.

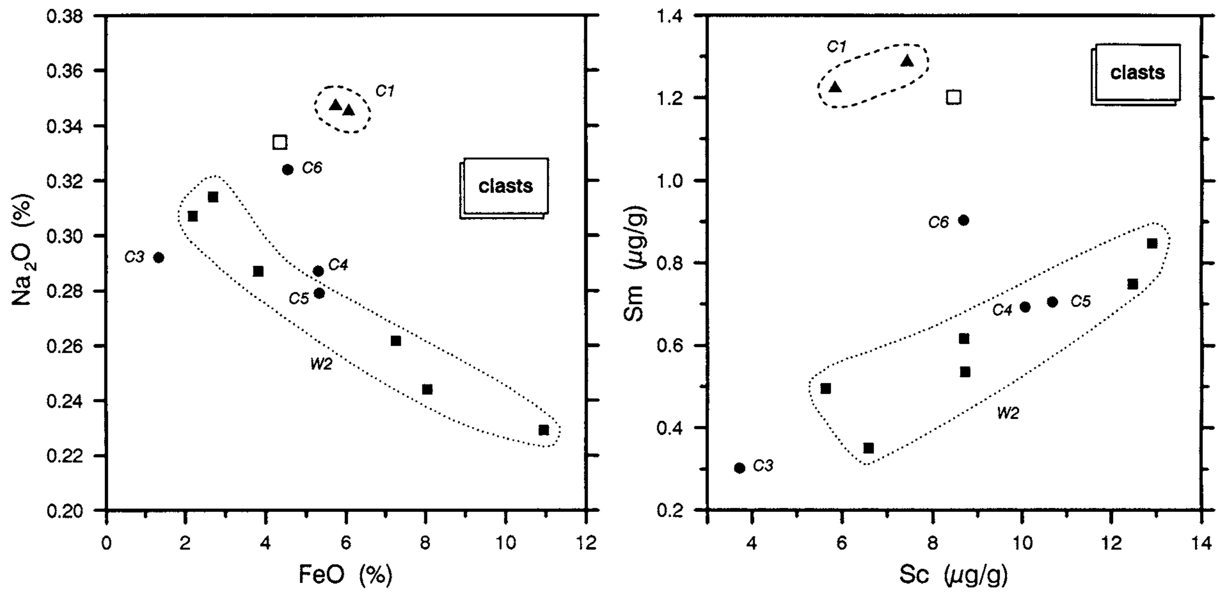

FIG. 10. Na, Fe, Sm, and Sc concentrations in clasts from MAC88104/5. The hollow square represents the bulk composition of the meteorite. The six subsamples (W2A-W2F) of clast W2 are shown as filled squares.

Nevertheless, compositions of highland soils and other polymict materials clearly demonstrate that relatively mafic, ferroan components must occur in highlands crust even at the Apollo sites (KOROTEV et al., 1980; KOROTEV, 1983; LINDSTROM and SALPAS, 1983; KOROTEV and HASKIN, 1988; WARREN, 1990). KOROTEV and HASKIN (1988) noted that mass balance for key elements (Si, Al, Fe, Mg, Sm, and Eu) in the average upper crust (based on many polymict samples

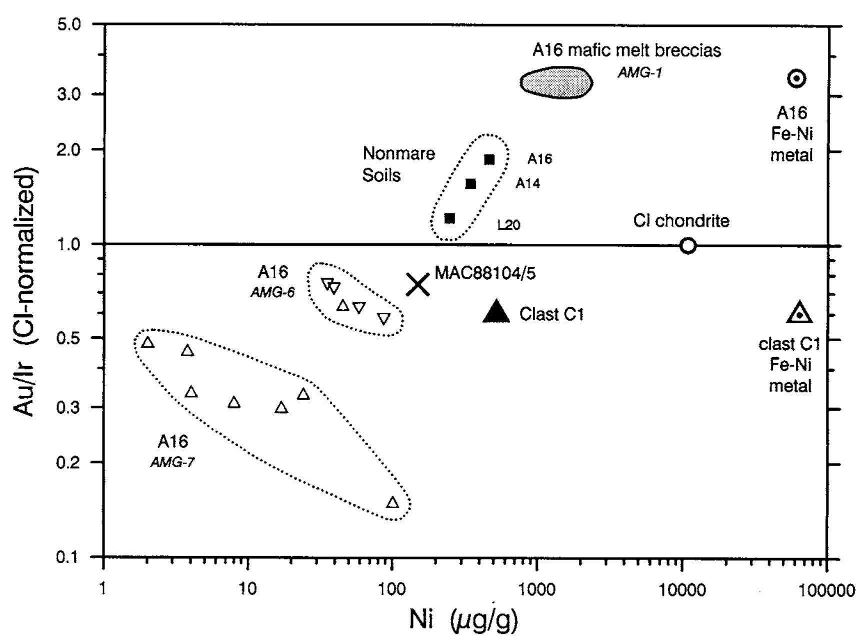

FIG. 11. CI-chondrite-normalized Au/Ir ratio as a function of Ni concentration for a variety of lunar samples. The highest Ni concentrations as well as the highest Au/Ir ratios in lunar rocks are found among the mafic impact-melt breccias at Apollo 16 (WASSON et al., 1975; KOROTEV, 1987b). These samples have large concentrations of Fe-Ni metal. This metal is the carrier of the siderophile-element signature of "ancient meteorite group 1" (AMG-1) (HERTOGEN et al., 1977). Apollo 16 soils contain both a component of these ancient impact-melt rocks and a component of chondritic material derived mainly from micrometeorites; thus, the Au/Ir ratio of the soils is greater than the chondritic value but less than that of the melt breccias. The subchondritic Au/Ir ratio of clast C1 is similar to that of some Apollo 16 samples (mostly highly feldspathic samples from North Ray Crater) which define AMG-6; however, these samples have much lower absolute concentrations of siderophile elements (see also PALME et al., 1991). Data from ANDERS and GREVESSE (1989); KOROTEV (1987a,b; 1990); JOLLIFF et al. (1991); unpubl. data, this lab (Luna 20); and HERTOGEN et al. (1977).

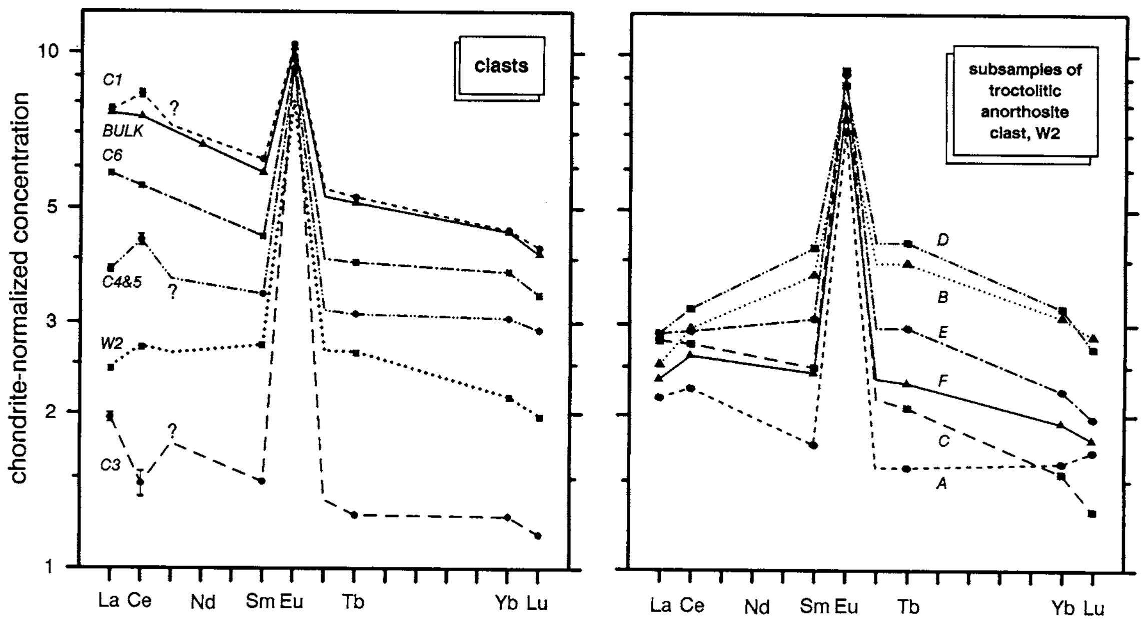

FIG. 12. Concentrations of REEs in clasts from MAC88104/5 normalized to chondritic abundances. The weighted-mean concentrations for clast W2 are plotted on the left, and the concentrations in the individual subsamples (W2A-W2F) are plotted on the right. Normalizing values: "Mean C1 chondr." concentrations of ANDERS and GREVESSE (1989) times 1.36 to convert to volatile-free basis. See Fig. 13 regarding Ce anomalies.

from different sites) could be attained with 72% ferroan-suite component modeled as a 29:71 mixture of plagioclase (ferroan anorthosite, sample 15415) and ferroan anorthositic norite (~68% plagioclase, sample 67215). Such a component contains 27.6% Al_2O_3, or about 78 wt% plagioclase (81 vol%). WARREN (1990) subsequently rediscovered that "mafic" ferroan anorthosite (MFA) containing 30.2% Al_2O_3 (mean of the four most mafic large anorthosites from Apollo 16) would provide a better mass balance for Al, Fe, and Mg in nonmare regolith samples than a ferroan-anorthosite component containing >99% plagioclase. This MFA component contains about 83.5 wt% (87 vol%) plagioclase. With 29% Al_2O_3 (81 wt% plagioclase), the bulk composition of MAC88105 is intermediate to these two estimates. Indeed, the precursor ferroan-suite rocks of MAC88104/5 are more typical of the lunar crust than plagioclase-rich extremes found at Apollo 16. MAC88104/5 and some other nonmare lunar meteorites contain clasts that are fragments of rocks that can be interpreted as common igneous products of a system that starts with plagioclase accumulation in a ferroan liquid, but with incomplete separation of the liquid and its crystalline products from the plagioclase.

Mineral clasts

The separate mineral clasts in thin section MAC88105,80 occur in proportions that are roughly those of noritic anorthosite. Plagioclase composes ~84 vol% of the clasts, and mafic minerals compose ~16%, with pyroxene and olivine in roughly equal proportions (opx > cpx). These proportions agree well with the mode as estimated above by normative analysis of the whole-rock composition. Mineral compositions in MAC88104/5 cover broad ranges (cf. NEAL et al., 1991; KOEBERL et al., 1991; DELANEY, 1990), but the majority cluster about those of the igneous clasts discussed above. These mineral fragments also are probably samples of the same precursor igneous rocks as the igneous lithic clasts. They also indicate a precursor assemblage that was, on average, ferroan and substantially more mafic than anorthosite (*sensu stricto*).

Polymict components

Fragments of impact-melt breccias compose the bulk of MAC88104/5 (KOEBERL et al., 1991; PALME et al., 1991; TAYLOR, 1991; LINDSTROM et al., 1991; and this work). The compositions of the matrices of these breccias may be taken to represent an average composition of their target rocks at the point of impact (e.g., MCCORMICK et al., 1989). On various two-element plots of major elements, these compositions define a roughly linear trend (Fig. 14). This could either be an igneous fractionation trend or indicate that the melt breccias are impact mixtures dominated by two components, one more anorthositic and the other more mafic. For the vitric-matrix breccia clasts, values of Mg' are rather uniform (0.58–0.63; Table 3) despite a factor of 2 variation in FeO concentration; thus, the range of compositions does not reflect a relict igneous fractionation trend but instead probably results from mixing. The mafic mixing component of the vitric-matrix breccia clasts may be a peritectic composition; the feldspathic component is not plagioclase, but a material of troctolitic anorthosite composition (Fig. 3b).

The trend for the MAC88105 glasses and feldspathic melt rock samples appears to differ from that of the more abundant vitric-matrix melt breccias (Fig. 3b). It is more similar to what we might expect for mixtures of cotectic liquids plus plagioclase. The trajectory resembles that for Apollo and Luna highlands soils, interpreted by KOROTEV et al. (1980) as corresponding to mixtures of plagioclase and cotectic mafic liquids.

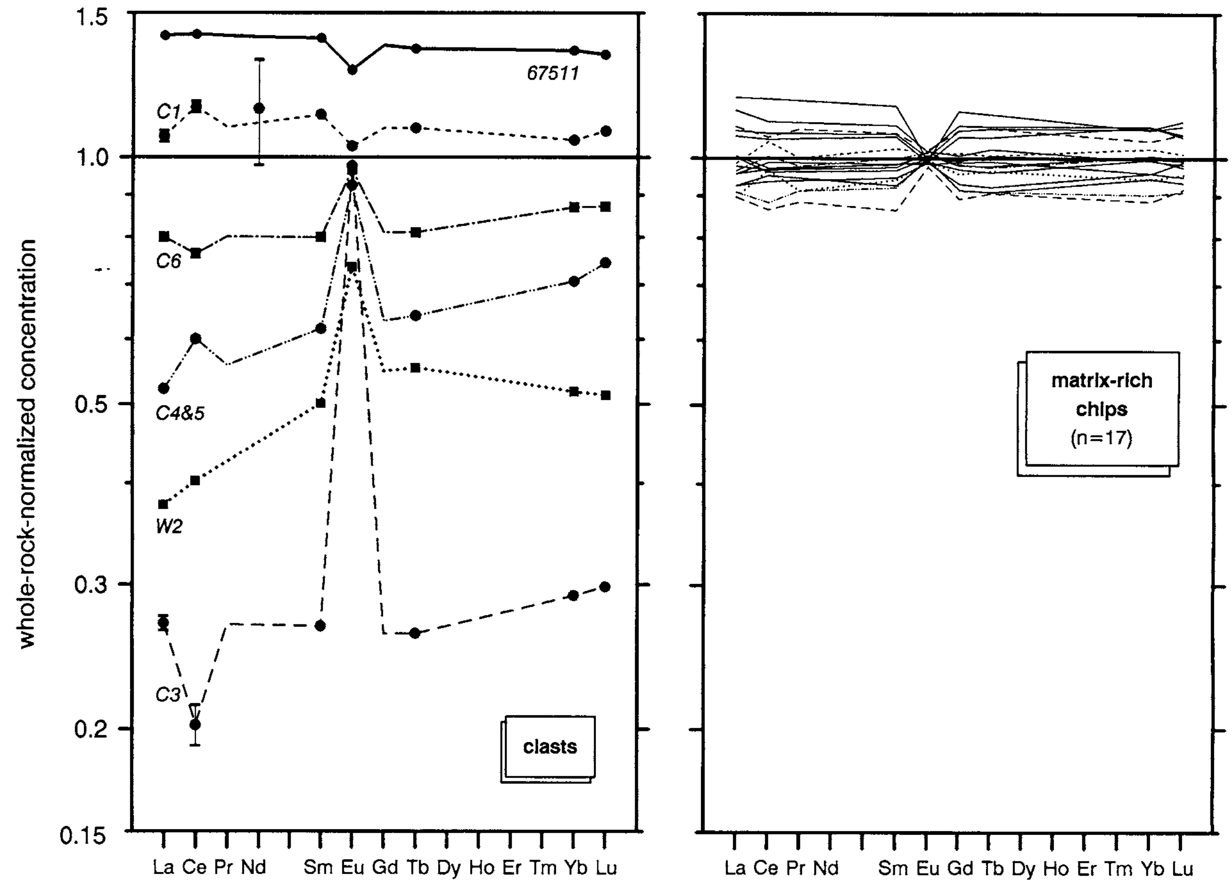

FIG. 13. Concentrations of REEs in clasts and matrix-rich chips from MAC88104/5 normalized to the weighted-mean concentrations of the matrix-rich chips. Some of the clasts (left) have Ce concentrations anomalously low or high compared to those of La and Sm (also, Fig. 12). Establishing the presence of a "Ce anomaly" based on INAA data is somewhat speculative because (1) Pr is not determined, (2) Nd is determined only imprecisely, and (3) the analytical signal for Ce is subject to certain interferences and complications that might lead to systematic error outside that predicted from simple counting statistics. Thus, as in Fig. 12, the lines have been drawn assuming that Pr and Nd values plot on the line connecting the La and Sm values, and that Ce alone behaves anomalously. (The measured Nd concentration with 1 σ error bars is plotted for clast C1; values for the other samples are even less precise.) For several reasons, we believe the anomalies to be characteristic of the samples, not the analysis. The magnitude of some of the anomalies is large compared to analytical uncertainty, which, for example, is <3% in the La/Ce ratio for clasts C4 and C5 (1 σ counting uncertainty). Defining Ce/Ce* as the observed Ce concentration divided by expected Ce concentration, based on linear interpolation between La and Sm, values of Ce/Ce* range from 0.80 for clast C3 to 1.20 for clast C4. For comparison, Ce/Ce* for the average of the matrix chips and the powder samples are 1.064 and 1.053, respectively. We do not take values of ~1.06 to imply that the bulk samples of the meteorites have slightly positive Ce anomalies because applying the same definition to a set of 11 Apollo 16 soils recently analyzed in this lab (KOROTEV, 1991) yields an average value of 1.066 for Ce/Ce*. Thus, the bulk meteorite samples have no Ce anomaly compared to Apollo 16 regolith (e.g., 67511, left). However, some of the individual matrix-rich chips do have small anomalies, both positive and negative (right). Ce/Ce* values range from 1.028 to 1.135 among the 17 chips. For comparison, the range observed in the 11 samples of Apollo 16 soil is only 1.053 to 1.076; the analytical precision for the two sets of samples is comparable.

The mafic impact-melt breccias in MAC88105 have matrix compositions that plot near the peritectic in the Fo-Si-An pseudoternary projection (Fig. 3). Their Mg′ values are low (0.49–0.57) compared to other melt breccias in the meteorite and to mafic melt rocks from Apollo sites ("low-K Fra Mauro" melt rocks, e.g., VANIMAN and PAPIKE, 1980), and their major element compositions do not follow the same linear trends as the more abundant vitric-matrix melt breccias (Fig. 14). For this reason, they probably represent a compositionally and spatially distinct igneous precursor that was not mixed with that of the vitric-matrix breccias by impact processes. Their ferroan compositions may reflect a VLT-basalt precursor (cf. LINDSTROM et al., 1986, esp. their Fig. 2L and Table 3 analysis) or its intrusive equivalent. The apparent trend observed in Fig. 14 for individual analyses of matrices of the mafic melt breccias suggests that their precursor had a plagioclase component significantly less anorthitic (lower Al_2O_3) than that of the other melt breccia groups.

Siderophile Elements in Clast C1

Because lunar impact melt rocks older than 3.9 Ga (debatably) do not occur, RYDER (1990) argues that bombardment of the lunar surface was light during its first 600 Ma

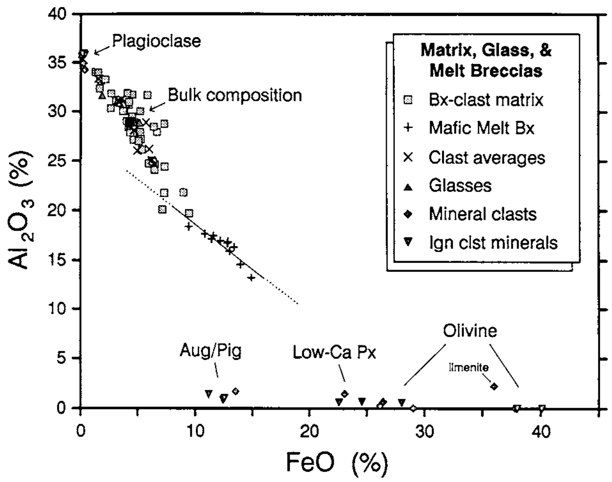

FIG. 14. Al_2O_3 and FeO concentrations from individual broad-beam analyses (EMP) of melt-breccia matrix materials, melt rocks, and glasses. Mineral compositions by EMP for reference. Bx = breccia.

and that "virtually all" of the large impacts occurred in a cataclysm between 3.8 and 3.9 Ga. He speculates the breakup of a large planetesimal within the Earth-Moon system as the cause of the cataclysm. If such a cataclysm occurred by such a process, then it is likely that fragments of the core of the planetesimal impacted the Moon at several locations.

The high concentrations of Fe-Ni metal (0.5–1%) in mafic impact-melt breccias from Apollo 16 led KOROTEV (1987b) to conclude that these breccias were formed by impact of a small number of metal-rich, possibly iron, meteorites. The metal composition, although not exactly matching that of any known class of iron meteorite, is similar to that of some irons. A characteristic of the metal is a high Au/Ir ratio (Fig. 10). Some investigators have questioned whether siderophile-element ratios of the impactor(s) are still preserved in the metal we find today (RINGWOOD et al., 1986; WÄNKE et al., 1990); however, no model has been proposed for how post-impact processes could generate such a large quantity of metal with a Au/Ir ratio three times the chondritic ratio (Fig. 10) from an impactor with a chondritic ratio. The combination of high Au/Ir ratios and high metal abundances are a peculiarity of the Apollo 16 melt rocks (HERTOGEN et al., 1977), and at least two compositionally distinct melts of this type occur (KOROTEV, 1987b). The most metal-rich type of melt rock at Apollo 16 appears to derive not from a large basin, but from an intermediate-size crater (50–150 km diameter, JAMES et al., 1984). Thus, the Apollo 16 melt rocks may have formed by impact into the Central Highlands of a few fragments of the core of a large planetesimal in which crystallization had fractionated Ir from Au. We might expect melt rocks from other locations on the Moon to contain metal with a complementary Au/Ir ratio if other fragments of that core impacted elsewhere on the Moon. No such rocks have been reported among the Apollo samples (except, perhaps, for those rocks representing ancient meteorite groups 6 and 7 of HERTOGEN et al., 1977; see Fig. 10), but as WARREN and KALLEMEYN (1991) remind us, the Apollo and Luna samples represent <10% of the lunar surface. The low-Au/Ir metal grains in melt-rock clast C1 from MAC88105 conceivably could derive from a different portion of the core of the planetesimal responsible for lunar cataclysm. This possibility requires that the Au/Ir ratio found in metal in melt rocks is not significantly different from that of the impactor and that the melt represented by breccia clast C1 has the same age as that of most Apollo impact melt rocks: 3.8–3.9 Ga.

Compositional Constraints on the Number of Lunar Impacts

Interpretation of noble-gas isotopes and cosmic-ray produced radionuclides indicates that the seven known specimens of meteorite from the lunar highlands (ALHA81005, Y791197, Y82192, Y82193, Y86032, MAC88104, and MAC88105) require at least two and possibly as many as four impacts on the lunar surface (EUGSTER, 1989; EUGSTER et al., 1991). These and other data indicate that Y82192 and Y82193 were clearly part of a single object until they encountered the Earth and that MAC88104 and MAC88105 are also fragments of a common object. Compositional and petrographic data have been used to constrain further the number of distinct regions of the lunar crust sampled by the lunar meteorites. When ALHA81005 and Y791197 were the only two lunar meteorites that had been studied, LINDSTROM et al. (1986) and LINDSTROM (1987) argued that they might be derived from the same region of the Moon by a single impact because compositional and petrographic differences such as clast distribution and Mg′ value (whole rock) between the meteorites, although substantial, are similar to those observed in breccias excavated by North Ray Crater, a 1-km crater at the Apollo 16 site. In response, WARREN and KALLEMEYN (1987) and WARREN et al. (1989) argued that fragmental breccias (North Ray Crater) are not comparable to regolith breccias (lunar meteorites) so that such a comparison is invalid. They argued that bulk compositional differences (primarily Mg′) among ALHA81005, Y791197, and Y82192 are so large that it was unlikely that the three meteorites all derived from the same lunar impact. WARREN and KALLEMEYN (1987) also contended that vertical variation in composition with depth in the uppermost 2 m of regolith is small, based on early studies of the Apollo 16 and 17 deep drill cores and, thus, that differences among the meteorites are not simply the result of variation in regolith composition with depth.

We show here that the compositional and petrographic diversity of Apollo 16 soils, particularly with depth, is nearly as great as that of the nonmare lunar meteorites. Comparison of nonmare lunar meteorites with Apollo 16 regolith is reasonable because (1) a large number of regolith samples was obtained at Apollo 16, including those from cores and those excavated from depth by North Ray Crater, and (2) like the nonmare lunar meteorites, but unlike regolith from other Apollo sites, the Apollo 16 regolith is highly feldspathic and nearly devoid of mare-derived material. For this reason, we briefly review data on Apollo 16 fines in an effort to correct some misconceptions. The Apollo 16 data serve as input to the following *gedanken* experiment: What if we could lithify the Apollo 16 regolith and then break the resulting breccia into pieces the size of the recovered lunar meteorites? This comparison relies primarily on soil from two regolith cores (0.6 and 2.2 m length) taken in the Cayley formation at the LM (lunar module) station at Apollo 16. Compositional variation with depth is great in these cores. For many elements, the range of variation in <1 mm fines from either of these cores exceeds that observed among ~40 samples of fines taken at the surface of the site over 8 km of lateral distance (KOROTEV, 1991).

In their study of modal petrography of the deep drill core, 60001-7, VANIMAN et al. (1976) recognized four "modal petrography units" which they designated MPU-A through MPU-D. In Fig. 7, the squares represent the average concentrations in a 5 cm-long plug of soil, i.e., a dimension similar to that of the MacAlpine Hills lunar meteorites, from each of the four MPUs of VANIMAN et al. (1976) and from one region in the 60009/10 drive tube. The four units of 60001-7 differ significantly in a number of petrographic, compositional, isotopic, and maturity parameters. For example, MPU-D was the most mature (GOSE and MORRIS, 1977), MPU-C was enriched in single crystals of plagioclase (VANIMAN et al., 1976), MPU-B contained the most mare material and a 10 cm-wide band enriched in siderophile elements (VANIMAN et al., 1976; KOROTEV, 1991), and MPU-A had unusually low $^{4}He/^{20}Ne$ and unusually high $^{40}Ar/^{36}Ar$ ratios (HEYMANN et al., 1978), an abundance of yellow glass (VANIMAN et al., 1976), and a large component of regolith breccia (KOROTEV, 1991).

These data are reviewed to show that within a 2 m soil profile there can be large variation in maturity, grain size, modal mineralogy, and elemental and noble-gas isotopic composition. When other Apollo 16 soils are considered (mostly those from North Ray Crater), the compositional range observed is equivalent to that of the nonmare lunar meteorites for many elements as well as Mg′ (Fig. 7). It is likely that impacts that launch lunar material to escape velocity sample a volume of crust larger than that of the impact that formed North Ray Crater (1 km diameter). Thus, the large variation in bulk Mg′ among the nonmare lunar meteorites is not in itself a strong argument that the meteorites derive from different impacts.

The Apollo 16 site was deliberately chosen to sample the contact between the Cayley and Descartes formations, and, thus, the Apollo 16 site is not a random site in the way that the source locations of lunar meteorites are random, and some compositional variability is to be expected in the regolith. Nevertheless, the LM-station cores, at least, are thought to be predominantly Cayley material, and there is no reason to believe that the compositional variation with depth observed in these relatively short cores is unusual for highlands regolith.

We do not present these data in order to argue that the seven specimens of nonmare lunar meteorite derive from only one or two lunar locations. Even without exposure data, the recent recognition of lunar meteorites of mare affinity is strong evidence that lunar material has made the Moon-Earth trip on several occasions (DELANEY, 1989; WARREN and KALLEMEYN, 1989; LINDSTROM and MARTINEZ, 1990; YANAI, 1990). Thus, the likelihood that the nonmare lunar meteorites represent perhaps as many as four discrete events now seems greater than it did several years ago. However, considering the large compositional and petrographic variations with depth observed in fines at the Apollo 16 site, the compositional and petrographic variations observed among the known samples of nonmare lunar meteorites do not support evidence that the meteorites derive from widely separated regions of the Moon.

CONCLUSIONS

MAC88104 and MAC88105 are paired fragments of a meteorite that contains a variety of materials including impact-melt breccias, igneous and metamorphosed breccia clasts, glass clasts and veins, mineral clasts, and extralunar meteoritic debris. The integrated study of all of these materials provides us with remarkably detailed information on the nature of the lunar crust from which this meteorite derived. Compositions of the bulk meteorite and its components indicate that it came from a region of the Moon's crust that was highly aluminous, low in incompatible trace elements, and markedly ferroan in character. As such, this meteorite and its components appear to be an excellent sample of what may be "typical" lunar highlands crust, practically uncontaminated by mare basalt and ITE-rich material (KREEP) that is associated with the large, nearside impact basins.

The high modal abundance of feldspathic impact-melt lithologies that occur as macroscopic and microscopic clasts in MAC88104/5 reflects an origin from a terrane dominated by impact debris, perhaps a regolith developed on a melt sheet. Igneous clasts include troctolitic anorthosite, anorthositic norite, gabbronorite, and anorthosite. These are ferroan and more mafic than typical ferroan-suite rocks known from Apollo samples. Similarities in mineral compositions and Mg′ suggest that the various igneous lithologies are petrogenetically related. Mineral clasts occur in the proportions of noritic anorthosite, the same as the normative mineralogy of the meteorite, based on its bulk composition. As a group, the mineral clasts are ferroan and consistent with derivation from a suite of igneous precursor rocks similar to the igneous clasts. This suite is more representative of the set of products expected from an igneous system crystallizing plagioclase from a ferroan liquid than are the highly feldspathic, ferroan rocks from Apollo 16.

Polymict materials are dominated by impact-melt breccias which also have low values of Mg′ and bulk compositions of noritic anorthosite. However, these materials are complex mixtures and may indicate three distinct suites of precursor materials: (1) the most abundant melt breccias, which on average have about the same composition as the bulk meteorite; (2) feldspathic glasses and melt rocks; and (3) mafic melt breccias that have an approximately peritectic composition in the Fo-Si-An system. Major-element compositional trends among the different polymict clasts suggest that these materials represent mixtures of very feldspathic material with several different kinds of mafic components, all of which, however, appear to be of ferroan character.

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REFERENCES

ANDERS E. and GREVESSE N. (1989) Abundances of the elements: Meteoritic and solar. *Geochim. Cosmochim. Acta* **53,** 197–214.

BENCE A. E. and ALBEE A. A. (1968) Empirical correction factors for the electron microanalysis of silicates and oxides. *J. Geol.* **76,** 382–403.

BISCHOFF A., PALME H., WEBER H. W., STÖFFLER D., BRAUN O., SPETTEL B., BEGEMANN F., WÄNKE H., and OSTERTAG R. (1987) Petrography, shock history, chemical composition and noble gas content of the lunar meteorites Yamato-82192 and -82193. *Proc. 11th Symp. Antarctic. Met.; Mem. NIPR* (Spec. Issue) **46,** 21–42.

BOYNTON W. V. and HILL D. H. (1983) Composition of bulk fragments and a possible pristine clast from Allan Hills A81005. *Geophys. Res. Lett.* **10,** 837–840.

BROWN R. W. (1977) A sample fusion technique for whole rock analysis with the electron microprobe. *Geochim. Cosmochim. Acta* **41,** 435–438.

DELANEY J. S. (1989) Meteorite (Elephant Moraine 87521) is the first lunar mare basalt from Antarctica. *Nature* **342,** 889–890.

DELANEY J. S. (1990) Preliminary petrographic data for MAC88105: Anorthositic microbreccia (abstr.). *Lunar Planet. Sci. XXI,* 273–274.

EUGSTER O. (1989) History of meteorites from the Moon collected in Antarctica. *Science* **245,** 1197–1202.

EUGSTER O., BEER J., BURGER M., FINKEL R. C., HOFMANN H. J., KRÄHENBÜHL U., MICHEL TH., SYNAL H. A., and WÖLFLI W. (1991) History of the paired lunar meteorites MAC88104 and MAC88105 derived from noble gas isotopes, radionuclides, and some chemical abundances. *Geochim. Cosmochim. Acta* **55,** 3139–3148 (this issue).

FLOSS C. and CROZAZ G. (1990) Antarctic weathering and REE remobilization in Antarctic eucrites (abstr.). *Papers Presented at the 15th Symposium on Antarctic Met.,* 75–77. NIPR.

FUKUOKA T., LAUL J. C., SMITH M. R., HUGHES S. S., and SCHMITT R. A. (1986a) Chemistry of Yamato-82192 and -82193 Antarctic meteorites (abstr.). *Papers Presented at the 11th Symposium on Antarctic Met.,* 40–42. NIPR.

FUKUOKA T., LAUL J. C., SMITH M. R., HUGHES S. S., and SCHMITT R. A. (1986b) Chemistry of Yamato-791197 Antarctic meteorite: Evidence for its lunar highlands origin. *Proc. 10th Symp. Antarctic Met.; Mem. NIPR* (Spec. Issue) **41,** 84–95.

GOODRICH C. A. and KEIL K. (1987) Mare basalts and other clasts in Yamato lunar meteorites Y-791197, -82192 and -82193. *Proc. 11th Symp. Antarctic Met.; Mem. NIPR* (Spec. Issue) **46,** 56–70.

GOODRICH C. A., TAYLOR G. J., KEIL K., BOYNTON W. V., and HILL D. H. (1984) Petrology and chemistry of hyperferroan anorthosites and other clasts from lunar meteorite ALHA81005. *Proc. 15th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **89,** C87–C94.

GOSE W. A. and MORRIS R. V. (1977) Depositional history of the Apollo 16 deep drill core. *Proc. 8th Lunar Sci. Conf.,* 2909–2928.

HASKIN L. A., LINDSTROM M. M., SALPAS P. A., and LINDSTROM D. J. (1981) On compositional variations among lunar anorthosites. *Proc. 12th Lunar Planet. Sci. Conf.,* 41–66.

HEAVILON C. F. and CROZAZ G. (1990) Ce anomalies in the Antarctic eucrite LEW 85300 (abstr.). *Lunar Planet. Sci. XXI,* 487–488.

HEYMANN D., JORDAN J. L., WALKER A., DZICZKANIEC M., RAY J., and PALMA R. (1978) Inert gas measurements in the Apollo-16 drill core and an evaluation of the stratigraphy and depositional history. *Proc. 9th Lunar Planet. Sci. Conf.,* 1885–1912.

HERTOGEN J., JANSSENS M.-J., TAKAHASHI H., PALME H., and ANDERS A. (1977) Lunar basins and craters: Evidence for systematic compositional changes of the bombarding population. *Proc. 8th Lunar Sci. Conf.,* 17–45.

JAMES O. B., FLOHR M. J., and LINDSTROM M. M. (1984) Petrology and geochemistry of lunar dimict breccia 61015. *Proc. 15th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **89,** C63–C86.

JAMES O. B., LINDSTROM M. M., and FLOHR M. K. (1989) Ferroan anorthosite from lunar breccia 64435: Implications for the origin and history of lunar ferroan anorthosites. *Proc. 19th Lunar Planet. Sci. Conf.,* 219–243.

JOLLIFF B. L., KOROTEV R. L., and HASKIN L. A. (1991) Geochemistry of 2–4-mm regolith particles from Apollo 14 soil (14161) and implications regarding igneous components and soil-forming processes. *Proc. 21st Lunar Planet. Sci. Conf.,* 193–219.

KALLEMEYN G. W. and WARREN P. H. (1983) Compositional implications regarding the lunar origin of the ALHA81005 meteorite. *Geophys. Res. Lett.* **10,** 833–836.

KOEBERL C. (1988) Trace element geochemistry of lunar meteorites Yamato-791197 and -82192. *Proc. NIPR Symp. Antarctic Met.* **1,** 122–134.

KOEBERL C., KURAT G., and BRANDSTÄTTER F. (1991) MAC88105—A regolith breccia from the lunar highlands: Mineralogical, petrological, and geochemical studies. *Geochim. Cosmochim. Acta* **55,** 3073–3087 (this issue).

KOROTEV R. L. (1981) Compositional trends in Apollo 16 soils. *Proc. 12th Lunar Planet. Sci. Conf.,* 577–605.

KOROTEV R. L. (1983) Compositional relationships of the pristine nonmare rocks to the highlands soils and breccias. In *Workshop on Pristine Highlands Rocks and the Early History of the Moon* (eds. J. LONGHI and G. RYDER); *LPI Tech. Rept. 83-02,* pp. 52–55. Lunar and Planetary Institute, Houston.

KOROTEV R. L. (1987a) The nature of the meteoritic components of Apollo 16 soil, as inferred from correlations of iron, cobalt, iridium, and gold with nickel. *Proc. 17th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **92,** E447–E461.

KOROTEV R. L. (1987b) The meteoritic component of Apollo 16 noritic impact melt breccias. *Proc. 17th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **92,** E491–E512.

KOROTEV R. L. (1990) Cobalt and nickel concentrations in the "komatiite component" of Apollo 16 polymict samples. *Earth Planet. Sci. Lett.* **96,** 481–489.

KOROTEV R. L. (1991) Geochemical stratigraphy of two regolith cores from the Central Highlands of the Moon. *Proc. 21st Lunar Planet. Sci. Conf.,* 229–289.

KOROTEV R. L. and HASKIN L. A. (1988) Europium mass balance in polymict samples and implications for plutonic rocks of the lunar crust. *Geochim. Cosmochim. Acta* **52,** 1795–1813.

KOROTEV R. L., HASKIN L. A., and LINDSTROM M. M. (1980) A synthesis of lunar highlands compositional data. *Proc. 11th Lunar Planet. Sci. Conf.,* 395–429.

KOROTEV R. L., LINDSTROM M. M., LINDSTROM D. J., and HASKIN L. A. (1983) Antarctic Meteorite ALHA81005—Not just another lunar anorthositic norite. *Geophys. Res. Lett.* **10,** 829–832.

LAUL J. C., SMITH M. R., and SCHMITT R. A. (1983) ALHA 81005 meteorite: Chemical evidence for lunar highlands origin. *Geophys. Res. Lett.* **10,** 825–828.

LINDSTROM M. M. (1987) How many impacts provided the lunar meteorites? Geochemical and petrological evidence (abstr.). *Meteoritics* **22,** 446.

LINDSTROM M. M. and MARTINEZ R. R. (1990) Lunar meteorite Y793274: A second basaltic breccia (abstr.). *Papers Presented at the 15th Symposium Antarctic Met.,* 114–115. NIPR.

LINDSTROM M. M. and SALPAS P. A. (1983) Geochemical studies of feldspathic fragmental breccias and the nature of North Ray Crater ejecta. *Proc. 13th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **88,** A671–A683.

LINDSTROM M. M., LINDSTROM D. J., KOROTEV R. L., and HASKIN L. A. (1986) Lunar meteorite Yamato-791197: A polymict anorthositic norite from the lunar highlands. *Proc. 10th Symp. Antarctic Met.; Mem. NIPR* (Spec. Issue) **41,** 58–75.

LINDSTROM M. M., KOROTEV R. L., LINDSTROM D. J., and HASKIN L. A. (1987) Lunar meteorites Y82192 and Y82193: Geochemical and petrologic comparisons to other lunar breccias (abstr.). *Papers Presented at the 11th Symposium Antarctic Met.,* 19–21. NIPR.

LINDSTROM M. M., WENTWORTH S., MARTINEZ R. R., MITTLEFEHLDT D. W., MCKAY D. S., WANG M., and LIPSCHUTZ

M. E. (1991) Geochemistry and petrology of the MacAlpine Hills lunar meteorites. *Geochim. Cosmochim. Acta* **55**, 3089–3103 (this issue).

MASUDA A., NAKAMURA N., KURASAWA H., and TANAKA T. (1972) Precise determination of rare-earth elements in Apollo 14 and 15 samples. *Proc. 3rd Lunar Sci. Conf.*, 1307–1313.

MASUDA A., TANAKA T., NAKAMURA N., and KURASAWA H. (1974) Possible REE anomalies of Apollo 17 REE patterns. *Proc. 5th Lunar Sci. Conf.*, 1247–1253.

MCCORMICK K. A., TAYLOR G. J., KEIL K., SPUDIS P. D., GRIEVE R. A. F., and RYDER G. (1989) Sources of clasts in terrestrial impact melts: Clues to the origin of LKFM. *Proc. 19th Lunar Planet. Sci. Conf.*, 691–696.

METZGER A. E., HAINES E. L., PARKER R. E., and RADOCINSKI R. G. (1977) Thorium concentrations in the lunar surface. *Proc. 8th Lunar Sci. Conf.*, 949–1000.

MITTLEFEHLDT D. W. and LINDSTROM M. M. (1991) Generation of abnormal trace element abundances in Antarctic eucrites by weathering processes. *Geochim. Cosmochim. Acta* **55**, 77–87.

NAVA D. F., LINDSTROM M. M., SCHUHMANN P. J., LINDSTROM D. J., and PHILPOTTS J. A. (1976) The remarkable chemical uniformity of Apollo 16 layered deep drill core section 60002. *Proc. 7th Lunar Sci. Conf.*, 133–139.

NEAL C. R., TAYLOR L. A., LUI Y., and SCHMITT R. A. (1991) Paired lunar meteorites MACC88104 and MAC88105: A new "FAN" of lunar petrology. *Geochim. Cosmochim. Acta* **55**, 3037–3049 (this issue).

OSTERTAG R., STÖFFLER D., BISCHOFF A., PALME H., SCHULTZ L., SPETTEL B., WEBER H., WECKWERTH G., and WÄNKE H. (1986) Lunar meteorite Yamato-791197: Petrography, shock history and chemical composition. *Proc. 10th Symp. Antarctic Met.; Mem. NIPR* (Spec. Issue) **41**, 17–44.

PALME H., SPETTEL B., WECKWERTH G., and WÄNKE H. (1983) Antarctic meteorite ALHA81005, a piece from the ancient lunar crust. *Geophys. Res. Lett.* **10**, 817–820.

PALME H., SPETTEL B., JOCHUM K. P., DREIBUS G., WEBER H., WECKWERTH G., WÄNKE H., BISCHOFF A., and STÖFFLER D. (1991) Lunar highland meteorites and the composition of the lunar crust. *Geochim. Cosmochim. Acta* **55**, 3105–3122 (this issue).

RINGWOOD A. E., SEIFERT S., and WÄNKE H. (1986) A komatiite component in Apollo 16 highlands breccias: Implications for the nickel-cobalt systematics and bulk composition of the Moon. *Earth Planet. Sci. Lett.* **81**, 105–117.

RYDER G. (1990) Lunar samples, lunar accretion and the early bombardment history of the Moon. *Eos* **71**, 313–323.

RYDER G. and NORMAN M. D. (1980) *Catalog of Apollo 16 rocks; NASA Curatorial Branch Publ. 52*, pp. 34–37. NASA/JSC, Houston.

RYDER G. and OSTERTAG R. (1983) ALHA 81005: Moon, Mars, petrography, and Giordano Bruno. *Geophys. Res. Lett.* **10**, 791–794.

SCORE R., LINDSTROM M., and MASON B. (1989) Collection, classification and description of MAC88104 and MAC88105—Two fragments of a lunar meteorite (abstr.). *Meteoritics* **24**, 324.

STÖFFLER D., MARVIN U. B., SIMONDS C. H., and WARREN P. H. (1980) Recommended classification and nomenclature of lunar highland rocks—a committee report. In *Proceedings of the Conference on Lunar Highlands Crust* (eds. J. J. PAPIKE and R. B. MERRILL), pp. 51–70. Pergamon Press.

TAKEDA H., MORI H., and TAGAI T. (1987) Mineralogy of lunar meteorites, Yamato-82192 and -82193 with reference to breccias in a breccia. *Proc. 11th Symp. Antarctic Met.; Mem. NIPR* (Spec. Issue) **46**, 43–55.

TAKEDA H., KOJIMA H., NISHIO F., YANAI K., LINDSTROM M. M., and Yamato Lunar Meteorite Consortium Group (1989) Preliminary report on the Yamato-86032 lunar meteorite: I. Recovery, sample descriptions, mineralogy and petrography. *Proc. NIPR Symp. Antarctic Met.* **2**, 3–14. NIPR.

TAYLOR G. J. (1991) Impact melts in the MAC88105 lunar meteorite: Inferences for the lunar magma ocean hypothesis and the diversity of basaltic impact melt. *Geochim. Cosmochim. Acta* **55**, 3031–3036 (this issue).

TREIMAN A. H. and DRAKE M. J. (1983) Origin of lunar meteorite ALHA81005: Clues from the presence of terrae clasts and a very low-titanium mare basalt clast. *Geophys. Res. Lett.* **10**, 783–786.

VANIMAN D. T. and PAPIKE J. J. (1980) Lunar highland melt rocks: Chemistry, petrology and silicate mineralogy. In *Proceeding of the Conference on Lunar Highlands Crust* (eds. J. J. PAPIKE and R. B. MERRILL), pp. 271–337. Pergamon Press.

VANIMAN D. T., LELLIS S. F., PAPIKE J. J., and CAMERON K. L. (1976) The Apollo 16 drill core: Modal petrology and characterization of the mineral and lithic component. *Proc. 7th Lunar Sci. Conf.*, 199–239.

WALKER D., LONGHI J., GROVE T. L., STOLPER E., and HAYS J. F. (1973) Experimental petrology and origin of rocks from the Descartes Highlands. *Proc. 4th Lunar Sci. Conf.*, 1013–1032.

WÄNKE H., DREIBUS G., and PALME H. (1990) Lunar siderophiles (abstr.). *Lunar Planet. Sci. XXI*, 1289–1290.

WARREN P. H. (1990) Lunar anorthosites and the magma-ocean plagioclase-flotation hypothesis: Importance of FeO enrichment in the parent magma. *Amer. Mineral.* **75**, 46–58.

WARREN P. H. and KALLEMEYN G. W. (1986) Geochemistry of lunar meteorite Yamato-791197: Comparison with ALHA81005 and other lunar samples. *Proc. 10th Symp. Antarctic Met.; Mem. NIPR* (Spec. Issue) **41**, 3–16.

WARREN P. H. and KALLEMEYN G. W. (1987) Geochemistry of lunar meteorite Yamato-82192: Comparison with Yamato-791197, ALHA81005, and other lunar samples. *Proc. 11th Symp. Antarctic Met.; Mem. NIPR* (Spec. Issue) **46**, 3–20.

WARREN P. H. and KALLEMEYN G. W. (1989) Elephant Moraine 87521: The first lunar meteorite composed of predominantly mare material. *Geochim. Cosmochim. Acta* **53**, 3323–3300.

WARREN P. H. and KALLEMEYN G. W. (1991) The MacAlpine Hills lunar meteorite and implications of the lunar meteorites collectively for the composition and origin of the Moon. *Geochim. Cosmochim. Acta* **55**, 3123–3138 (this issue).

WARREN P. H., JERDE E. A., and KALLEMEYN G. W. (1989) Lunar meteorites: siderophile element contents, and implications for the composition and origin of the Moon. *Earth Planet. Sci. Lett.* **91**, 245–260.

WASSON J. T., CHOU C.-L., ROBINSON K. L., and BAEDECKER P. A. (1975) Siderophiles and volatiles in Apollo-16 rocks and soils. *Geochim. Cosmochim. Acta* **39**, 1475–1485.

YANAI K. (1990) Asuka-31: Gabbroic cumulate originated from lunar mare region (abstr.). *Papers Presented at the 15th Symposium Antarctic Met.*, 119–121. NIPR.