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Paired lunar meteorites MAC88104 and MAC88105: A new "FAN" of lunar petrology*

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Abstract—New lunar meteorite MAC88104/5 represents an exciting new opportunity to study a potentially unsampled region of the Moon. We have analyzed six thin sections by electron microprobe and three bulk samples by Instrumental Neutron Activation (INA) in order to determine the chemical characteristics of this new lunar sample. Lunar meteorite MAC88104/5 is dominated by lithologies of the ferroan anorthosite (FAN) suite and contains abundant granulitized highland clasts, devitrified glass beads of impact origin, and two small clasts which appear to be of basaltic origin. One of these "basaltic" clasts (clast E in MAC88105,84) is probably mesostasis material, whereas the second larger clast (clast G) may be similar to the Very Low-Ti (VLT) or low-Ti/high-alumina mare basalts. Impact melt clasts MAC88105,69 and ,72 have major and trace element compositions similar to the bulk meteorite. There is little evidence of any LKFM (Low-K Fra Mauro or low-K KREEP) contribution to this meteorite, as MAC88104/5 and other brecciated lunar meteorites are Fe-rich and poor in the incompatible elements relative to Apollo 16 regolith and feldspathic breccias. While the exact site of origin for the lunar meteorites cannot be pinpointed, it is evident that they were derived from a relatively KREEP-free ferroan anorthosite terrain.

INTRODUCTION

THE SIGNIFICANCE OF the lunar meteorites is that they give us the potential to study as yet unsampled regions of the Moon and thereby yield essential data towards a better understanding of lunar evolution. Furthermore, they are the only source of new lunar samples available to the scientific community. The discovery of lunar meteorite MAC88104/5 brings to a total of eleven "new" lunar samples that have been recognized. Of these, seven are anorthositic breccias (ALHA81005, Y791197, Y82192, Y82193, Y86032, MAC88104, MAC88105; e.g., MARVIN, 1983; LINDSTROM et al., 1986; WARREN and KALLEMEYN, 1987), two are mare basaltic breccias (Y793274 and EET87521), and two are mare gabbros (ASUKA31 and Y793169) (WARREN and KALLEMEYN, 1989; DELANEY and SUTTON 1990; WARREN et al., 1990; YANAI, 1990).

Meteorite MAC88105 weighs 662.5 g (SCORE et al., 1989) and has been described as being of lunar origin due to its anorthositic and brecciated nature and its oxygen isotope composition ($\delta^{18}O = 5.5‰$; $\delta^{17}O = 2.7‰$; CLAYTON, 1989). It has been paired with the smaller (61.2 g) MAC88104. MAC88104/5 was recovered by the 1988 ANSMET team. Both MAC88104 and 88105 contain abundant angular, feldspathic clasts and fine-grained gray, black, and beige clasts (SCORE, 1989). The purpose of this paper is to present mineral and whole-rock data from MAC88104/5, to investigate the lunar lithologies contained by this meteorite, and to postulate the type of site from which this lunar sample was derived.

For our investigation, we received three chips for INA and corresponding thin sections (in parentheses): MAC88105,67(,96); ,69(,92); and ,72(,94). These samples were described by the JSC Curatorial Facility as follows: MAC88105,67(,96) is a white clast plus matrix, MAC88105,69(,92) is comprised of impact-melt chips plus matrix, and MAC88105,72(,94) is an impact melt clast plus matrix. Also allotted to us were thin sections MAC88104,29 and MAC88105,84; ,93; ,96; ,99. MAC88104,29 and 88105,84 were described by the Meteorite Curatorial Facility as being matrix samples. MAC88105,93 was described as a glassy impact melt plus matrix; 88105,96 as an anorthositic clast plus matrix; and 88105,99 as an impact melt clast plus matrix.

PETROGRAPHY AND MINERAL CHEMISTRY

This study concentrated upon the lithic rather than mineral clasts of MAC88104/5 in order to evaluate their composition and provenance. We will discuss each thin section individually in order to highlight its pertinent features. Mineral analyses were undertaken at the University of Tennessee on a CAMECA SX-50 Electron MicroProbe (EMP) using a 15 kV accelerating voltage and a 100 uA filament current. Beam current used for all phases was 30 nA, except for glasses and feldspars when 20 nA was employed (measured using a Faraday cup); counting times were 20 secs. All data were reduced using standard ZAF procedures.

Bulk Samples

MAC88104,29

MAC88104,29 (1 cm × 0.8 cm) contains several clasts and abundant mineral fragments set in a dark brown, opaque, glassy matrix. The distribution of the largest fragments is given in Fig. 1. Mineral fragments range in size from <0.1 mm up to 0.8 mm and their abundances generally follow the order plagioclase > pyroxene > olivine. Some larger

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

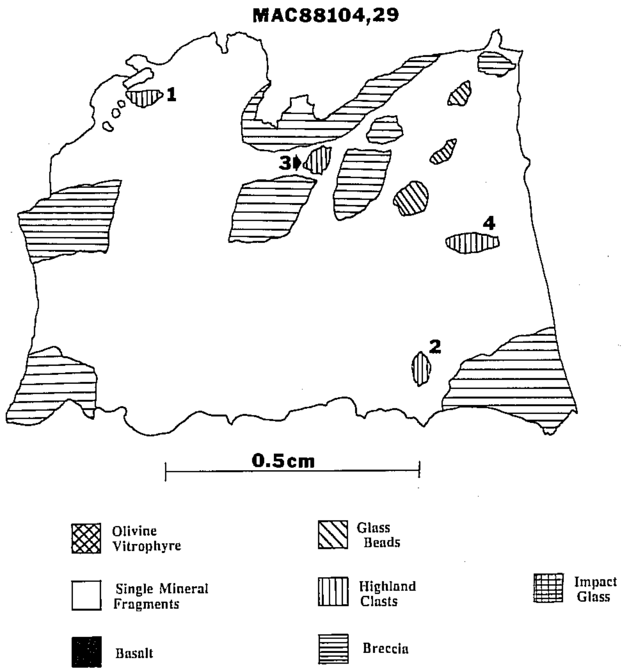


FIG. 1. Map of thin section MAC88104,29.

fragments of lithic clasts with annealed textures are present (up to 1.5 mm). Clasts of a darker and less clast-rich breccia range up to 2 mm diameter. One devitrified glass bead (~0.6 mm) is present (Fig. 2a). It is felsic (25.9 wt% Al_2O_3; 14.7 wt% CaO; 69.9% normative An) with little range in composition on the basis of six analyses. Other glass patches are elongated and exhibit less pronounced margins with the matrix (Fig. 2a). These glasses also exhibit little compositional variation; they are olivine normative but felsic in composition (19.4 wt% Al_2O_3; 12.6 wt% CaO; 50.6% normative An on the basis of six analyses). Four granulite clasts are present in this thin section (Figs. 1 and 2b). These are dominated by plagioclase (An_{95-97}, eight analyses from each clast), with subordinate amounts of pyroxene and olivine, generally $\ll$0.1 mm. Sizes of individual granulite clasts are between 0.2 and 0.5 mm. Generally, pyroxene is more abundant than olivine, but the small grain size makes accurate point counting difficult. Also, the fine-grained and recrystallized nature of all granulites reported here made evaluation of core-to-rim zonation extremely difficult. Granulite 1 is a noritic anorthosite, containing olivine of Fo_{62-63} (five analyses) and pigeonite [MG# = 66–67 and $Wo_{8-12}En_{59-60}Fs_{29-31}$; MG# = 100*Mg/(Mg + Fe), eleven analyses]. Plagioclase is uniform in composition (An_{96-97}, 12 analyses). Granulite 2 is a gabbroic anorthosite containing two pyroxenes ($Wo_{34-35}En_{43-45}Fs_{20-21}$, MG# = 68–69, five analyses; $Wo_{11}En_{57}Fs_{32}$, MG# = 64, two analyses), olivines of intermediate composition (Fo_{57-58}, six analyses), and a plagioclase of almost constant composition (An_{96}, eight analyses). Granulite 3 is a noritic anorthosite, containing pyroxenes ranging from orthopyroxene to pigeonite ($Wo_{4-11}En_{53-59}Fs_{33-38}$, MG# = 61–62, nine analyses) and olivines of intermediate composition (Fo_{50-53}, eight analyses). Again, plagioclase is almost constant in composition (An_{96-97}, fourteen analyses). Granulite 4 is also a noritic anorthosite with pigeonite ($Wo_{11-17}En_{56-62}Fs_{26-27}$, MG# = 69–70, eleven analyses) and olivines which are more forsteritic (Fo_{64-65}, five analyses) than in granulites 2 and 3. Plagioclase exhibits the widest range of composition of the four granulites studied in this section (An_{95-97}, fifteen analyses). Estimated modes for these four granulites can be found in Table 1. From these limited analyses, the compositions of individual mineral grains within 88104,29 appear to be similar to those for the lithic clasts. The small range in mineral compositions may suggest that these may be monomict samples which have experienced cataclasis, or were polymict samples which equilibrated during metamorphism. More definitive conclusions cannot be made without siderophile element data.

MAC88105,84

MAC88105,84 (1 cm × 0.75 cm) is similar to 88104,29 in that it contains several clasts and abundant mineral fragments set in a dark brown, opaque, glassy matrix. The distribution of the largest fragments is given in Fig. 3 and the estimated modes are given in Table 1. Abundances of mineral fragments are again generally plagioclase > pyroxene > olivine with grain sizes varying from <0.1 mm up to 0.8 mm. Some larger fragments of lithic clasts of impact, highland, and mare affinities are present (up to 2 mm) and exhibit annealed textures (highland and impact melt) or igneous textures (basaltic clasts). For MAC88105,84, the largest (clast B) is a vitrophyric basalt (30 × 20 mm; Fig. 2c) composed of olivine (0.1 mm), plagioclase (0.15 mm), and opaque glass. Three blocky plagioclase phenocrysts (up to 0.3 mm) are present. Groundmass plagioclases have a composition of An_{95-96}; the larger plagioclase phenocrysts have more calcic cores (An_{98}), but rims are the same composition as the groundmass. Olivines range in composition from Fo_{71} to Fo_{74}. The glass is enriched in Ca- and Al-rich. MG# varies from 56, where the glass is almost pure plagioclase, to 74. Overall texture, coupled with the presence of plagioclase phenocrysts (a rare phenomenon in lunar basalts), indicates it may represent a devitrified impact melt similar to those described by SHERVAIS et al. (1988).

Four granulitic highlands clasts were analyzed by EMP (clasts A, C, D, F; Fig. 3); all are noritic anorthosites ranging from 0.3–1 mm. These granulitic clasts are petrographically similar to the granulites in 88104,29 (Fig. 2d). Clast A contains olivine (Fo_{66-67}, eight analyses) and pigeonite ($Wo_{9-11}En_{60-63}Fs_{26-34}$, MG# = 69–70, twelve analyses), set in a plagioclase matrix of anorthosite-rich composition (An_{95-98}, fifteen analyses). Clast C contains olivine of more variable composition (Fo_{60-73}, ten analyses), but pyroxene (Wo_{10-11} $En_{58-60}Fs_{29-32}$, MG# = 65–6, eleven analyses) and plagioclase (An_{96-97}) exhibit somewhat restricted compositions. Clast D is a granulite containing only one olivine grain (Fo_{53}, four analyses) and pyroxene ($Wo_2En_{51}Fs_{47}$, MG# = 52, three analyses), which exhibit little core-to-rim variation. Plagioclase is anorthositic (An_{96-97}, ten analyses) with little core-to-rim zonation. Clast F comprises predominantly of plagioclase (An_{96-98}, nine analyses), with olivine (Fo_{49-50}, five analyses) and pyroxene ($Wo_{8-12}En_{50-55}Fs_{33-42}$, MG# = 59–61, eight analyses).

Two small basaltic clasts (0.2 × 0.2 mm and 0.3 × 0.3 mm) are also present in 88105,84 (clasts E and G). The largest (clast G; Fig. 2e) is composed of pyroxene, olivine, plagioclase, and ilmenite (MgO = 0.4–0.5 wt%, four analyses). These phases are fine-grained (largest = 0.1 mm) and exhibit no signs of cataclasis. Boundaries with the breccia are distinct, and the clast stands out because of the high relief of the mafic phases. Plagioclase exhibits little compositional variation (An_{95-98}) with the less calcic compositions found on the rims of the mineral grains. Olivine compositions vary between Fo_{51} and Fo_{69} (seven analyses) and exhibit core-to-rim zonation towards the more Fe-rich compositions. Small (<0.05 mm) grains of almost pure fayalite (Fo_{1-2}, three analyses) are found as interstitial phases between the major minerals. Pyroxenes also exhibit a range in compositions from augite ($Wo_{34}En_{40}Fs_{26}$) toward pyroxferroite ($Wo_{26}En_{15}Fs_{59}$; Fig. 4a). These pyroxenes yield a range in MG# of 18–67 (five analyses) not all accounted for by core-to-rim zonation. The smaller basalt (clast E) is situated next to a small granulite clast of similar size (Fig. 2f). It comprises of interlocking pyroxene, olivine, and plagioclase, and also SiO_2 (cristobalite?) and interstitial opaque glass, but no opaque minerals. No signs of cataclasis are evident, and the boundaries with the matrix are sharp. Mineral compositions exhibit more of a range than in the other basaltic clast. This is most marked in the pyroxenes (eight analyses) range from pigeonite ($Wo_9En_{61}Fs_{30}$) to pyroxferroite (~$Wo_{23}En_7Fs_{70}$; Fig. 4b). The only olivine present is extremely Fe-rich (Fo_{6-9}, four analyses) and is associated with the silica phase and the opaque glass.

Four small glass beads are present in 88105,84 (see labels in Fig. 3), with the largest reaching 0.15 mm in diameter. These are more compositionally variable than those in 88104,29, but generally are felsic in composition (19–27 wt% Al_2O_3, 12–16 wt% CaO, and 49–71% normative An, nine analyses). Also, glass bead number 4 contains a halo of sulfide and FeNi metal (Fig. 2g; Fig. 3). All of these glasses have feathery devitrification textures.

Clasts

MAC88105,67 and ,96

We made our own probe mount (,67) of our bulk clast sample. Small (<0.1 mm) mafic minerals are poikilitically enclosed in plagioclase. Thin section 88105,96 is a chip ~0.4 × 0.4 cm, made up of two thirds breccia matrix and one third a gabbroic anorthosite clast (W4 of LINDSTROM et al., 1991). Two types of breccia are present; that nearest the clast is glassy and opaque with only a few angular mineral clasts (0.1–0.3 mm), with a plagioclase mantle ~0.6 mm wide around the clast. This opaque, glassy breccia abruptly changes into a more clast- and mineral-rich breccia, which also contains a secondary breccia clast (0.6 mm × 0.3 mm) of the type mantling the gabbroic anorthosite. Two devitrified glass beads (both ~0.15 mm diameter) are present. Most of the angular mineral fragments (~0.1 mm) in this portion of breccia are plagioclase with minor pyroxene. The clast (~2 mm × 0.7 mm) in Fig. 2k is dominated by plagioclase (~70%; Table 1; An_{96-98}, nineteen analyses) which has been cataclasized and recrystallized. The mafics (~30%; Table 1) appear to be interstitial (intercumulus?) (Fig. 2k), but whether this is a primary igneous or a secondary metamorphic (impact) texture is uncertain. The pyroxenes and olivines range in size from 0.05 mm up to 0.2 mm. Compositions of the mafic silicates are: olivine = Fo_{55-58}; orthopyroxene = $Wo_{3-4}En_{70-68}Fs_{27-28}$, MG# ~ 65; augite = $Wo_{40-44}En_{42-45}Fs_{12-18}$, MG# = 71–79 (eight analyses each). Native Fe and troilite are small (~0.005 mm or less) and disseminated throughout the thin section. The chemistry of the major minerals in this clast appears to be out of equilibrium, which suggests it is neither a true plutonic sample nor a metamorphosed granulite.

MAC88105,69 and ,92

The bulk sample and probe mount (,69) consist of impact melt plus matrix. We did not undertake any probe analyses on this sample. However, MAC88105,92 is a 0.5 × 0.5 cm chip of breccia matrix (G4 of LINDSTROM et al., 1991). Two types of matrix are present. Two-thirds of the slide is comprised of 80% opaque glass, devitrified in places, containing angular mineral clasts of plagioclase (up to 0.4 mm) and rare pyroxene fragments (<0.1 mm); the remaining one-third of the slide is composed of a relatively glass-poor breccia containing abundant mineral fragments, the largest being plagioclase (up to 0.5 mm) exhibiting undulose extinction and dislocated exsolution lamellae. The first breccia type is separated from the second breccia by a brown, semi-opaque glass (Fig. 2h) which contains mineral fragments of mostly pyroxene (~0.1 mm). As no lithic clasts were present in this sample, we did not analyze it with the electron microprobe.

MAC88105,72 and ,94

This sample was allotted to us for INA and we made a thick probe mount of five chips for electron microprobe analysis. Our probe mount revealed granulite clasts in two of the five chips. These had identical chemistry and appear to be parts of clast G6 (LINDSTROM et al., 1991). Textures are similar to those of other granulites reported here, namely small mafics (≪0.05 mm) poikilitically enclosed in plagioclase. This clast is composed of plagioclase (An_{96-98}, thirteen analyses), olivine (Fo_{66-67}, seven analyses), pigeonite ($Wo_{9-12}En_{63-64}Fs_{26-27}$, MG# = 70–71, five analyses), and augite (one grain was found of composition $Wo_{36}En_{47}Fs_{17}$, MG# = 73, three analyses). Thin section 88105,94 also contains a granulite clast (Fig. 2i) which dominates the 0.3 × 0.5 cm slide. It is comprised of small (<0.2 mm) plagioclase grains (~60%; Table 1, An_{96-97}) and even smaller (~0.01 mm) mafics (~36%; Table 1). The clast has been heavily cataclasized with the mafic grains forming unevenly distributed clots. Mafic minerals are generally homogeneous olivines (Fo_{67-68}, five analyses) and pyroxenes ($Wo_{18-22}En_{54-56}Fs_{24-26}$, MG# = 68–69, seven analyses). Ilmenite (~4%; Table 1) of similar size to the mafic silicates is also present as a minor mineral (MgO = 4.5–5.0 wt%, four analyses). No metal or troilite was observed. The rest of the thin section is comprised of clast- and mineral-fragment-rich breccia matrix, and the boundary between the clast and breccia is abrupt and well defined. Mineral fragments are angular and

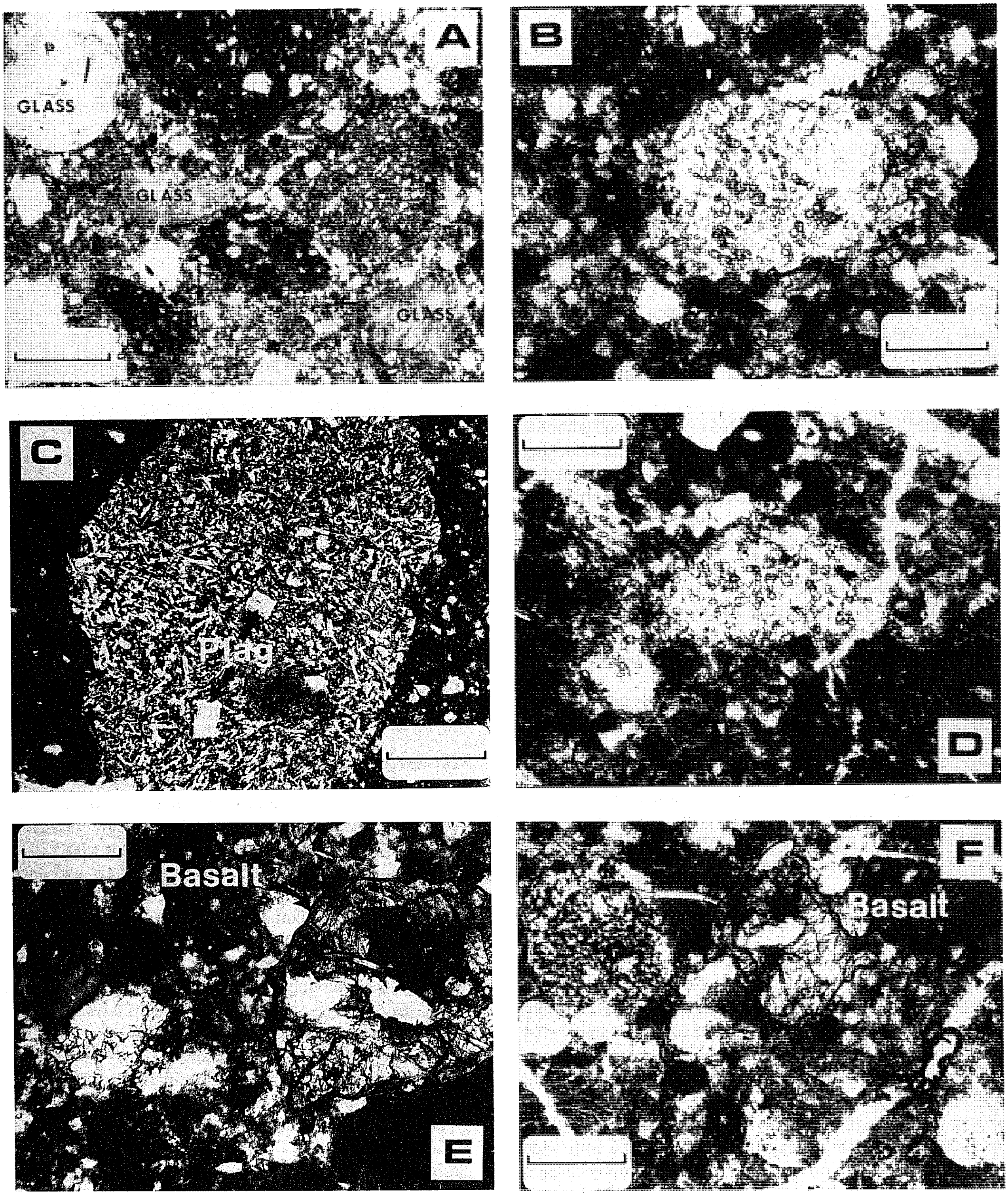
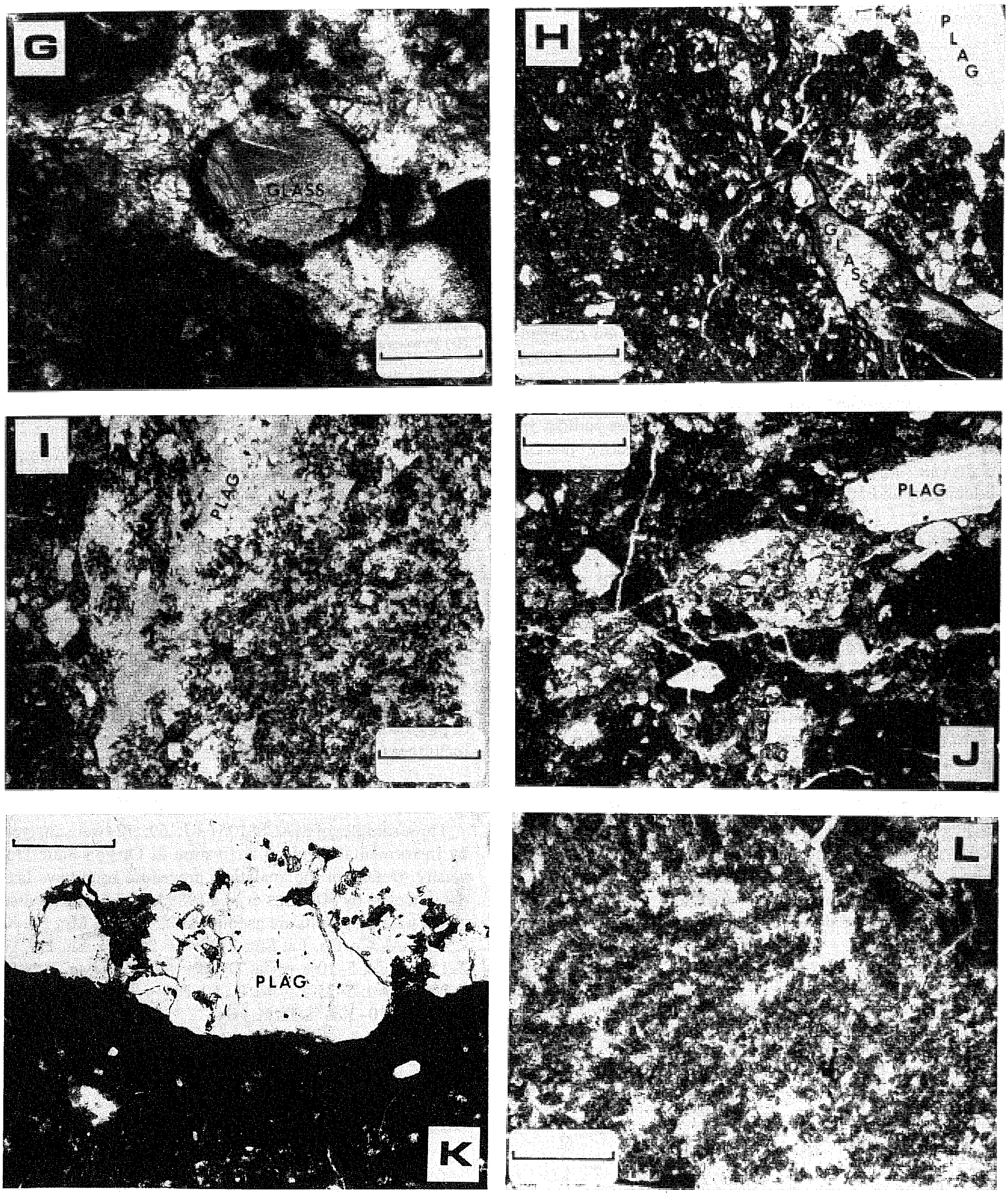


FIG. 2. Series of photomicrographs demonstrating the various clast textures in lunar highland meteorite MAC88104/5. A = devitrified glass beads in thin section MAC88104,29. The best example is in the upper left-hand corner. Glass fragments in the center and bottom right-hand corner of the photomicrograph exhibit more diffuse boundaries and care less rounded. Scale bar represents 0.5 mm. B = Granulite clast, dominated by plagioclase, in MAC88104,29. Scale bar represents 0.25 mm. C = Vitrophyric melt clast in MAC88105,84. Note the blocky plagioclase phenocrysts and general predominance of plagioclase in the clast. Scale bar represents 0.5 mm. D = Plagioclase-dominated granulite clast in MAC88105,85. Scale bar represents 0.25 mm. E = Basaltic clast G (to right) and granulite clast (to left) in MAC88105,84. Note the coarse nature of the mafics in the basalt clast. F = Devitrified glass bead (bottom right),



mafic-rich granulite clast (top left) and basaltic clast E (top center) in MAC88105,84. Scale bar represents 0.25 mm. G = Devitrified glass bead with native Fe and troilite rim. Scale bar represents 0.125 mm. H = Clast-rich and clast-poor breccia separated by glass in MAC88105,92. Scale bar represents 0.5 mm. I = Large granulite clast with irregular distribution of mafics in MAC88105,94. Scale bar represents 0.5 mm. J = Large single plagioclase crystal (top right) and two granulite clasts in MAC88105,93. Scale bar represents 0.5 mm. K = Gabbroic anorthosite clast in MAC88105,96. Note the clast-poor breccia immediately adjacent to the clast, grading into more clast-rich breccia. L = Mafic-rich granulite clast, with ilmenite, in MAC88105,99. Scale bar represents 0.25 mm.

TABLE 1: Estimated Modes (%) of the Lithic Clasts

Clast	Plagioclase	Pyroxene	Olivine	Ilmenite	"Mafics"*	Silica	Glass
88104,29:1	80				20		
2	85				15		
3	86				14		
4	88				12		
88105,84:A	65				35		
B	30				50		20
C	35				65		
D	40				60		
E	20	60	15			5	
F	55				45		
G	20	40	35	5			
,67/,96	70				30		
,72/,94	60			4	36		

* = where granulites are extremely fine-grained, it is difficult to identify pyroxene and olivine as individual phases, so they were combined under the blanket term "Mafics".

dominated by plagioclase (up to 0.2 mm), but a few rounded olivine grains (~0.05 mm) are also present. Occasionally, rounded inclusions of pyroxene (<0.05 mm) are present within the plagioclase mineral fragments. Within this breccia matrix is a small (0.8 × 0.5 mm) granulite clast, similar to the ones described above. Four dark matrix (glassy) breccia clasts (all ~0.4 × 0.3 mm) are also present, containing no lithic clasts and few angular mineral fragments.

MAC88105,93

This thin section is a 1 × 1 cm chip of matrix material (Fig. 5) (clast D3 of LINDSTROM et al., 1991). Angular mineral fragments (<0.1 mm) are set in a finer-grained, dark brown/opaque groundmass. Plagioclase is predominant (up to 1 mm; Fig. 2j), followed by pyroxene and olivine. Composite clasts are present, mostly of other breccia types (Fig. 5). These breccia clasts are rounded (up to 1 mm) and contain more opaque glass and less mineral fragments. Other clasts are rounded granulites (Fig. 2j), dominated by plagioclase, with olivine and/or pyroxene (<0.05 mm). The larger granulite clast (0.5 × 0.3 mm) contains olivine (Fo_{65-66}, four analyses), pyroxene ($Wo_{8-10}En_{63-64}Fs_{27-28}$, MG# = 69–70, seven analyses), and plagioclase (An_{96-97}, eleven analyses). The smaller (0.3 × 0.15 mm) granulite clast is comprised only of olivine (Fo_{75-76}, six analyses) and plagioclase (An_{97-98}, twelve analyses). In both cases plagioclase is the dominant mineral.

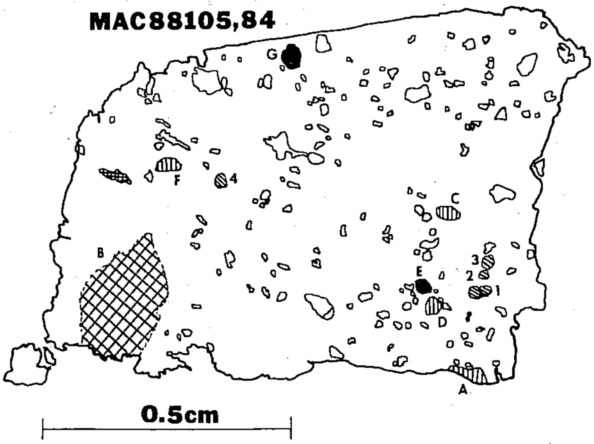


FIG. 3. Map of thin section MAC88105,84. Shading as in Fig. 2.

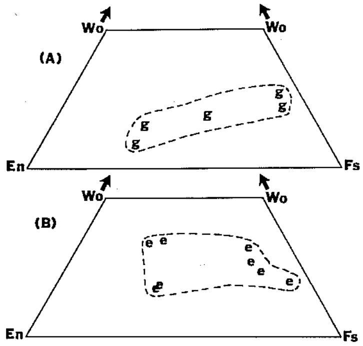


FIG. 4. Pyroxene compositions from two potential basaltic clasts in MAC88105,84: (a) Pyroxene compositions from basaltic clast G; (b) Pyroxene compositions from basaltic clast E.

MAC88105,99

This thin section is a single chip ~0.4 × 0.2 cm of breccia matrix and a granulite clast (2 × 0.5 mm; clast G2 of LINDSTROM et al., 1991). The clast is composed of small mafic minerals (0.005–0.01 mm) and plagioclase (An_{97}, ten analyses; Fig. 21). The mafic silicates (olivine ~Fo_{70-75} and homogeneous pigeonite, six analyses each) form irregularly distributed clots. Ilmenite is present (MgO ~ 4.5 wt%, four analyses), being of similar size to the mafic silicates. The plagioclase is extremely cataclasized and recrystallized, and the boundary with the breccia is diffuse, but discernable. The breccia is comprised of angular plagioclase (up to 0.15 mm) and pyroxene (≤0.1 mm). Also, there are bimineralic grains of plagioclase (up to 0.2 mm) with what appear to be olivine inclusions (≤0.05 mm). No native Fe or troilite was observed.

WHOLE-ROCK CHEMISTRY

Three samples of MAC88105 (,67; ,69; ,72) were analyzed by Instrumental Neutron Activation at Oregon State University. Details of the analytical procedure used have been documented by HUGHES et al. (1989). Uncertainties associated with the results are as follows: <2% = Fe, Mn, Na, Sc; <5% = Al, Cr, Co, La, Sm; 2–10% = Eu, Yb, Lu, Hf, Th; 2–15% = Ce; 5–10% = Ca, Dy, Ta; 5–15% = Mg, Nd, Tb; 5–20% = Au; 5–25% = Ni, Ir; 10–20% = V, Sr, U; 10–25% = Ba, Cs; 10–30% = Ti, K, Rb.

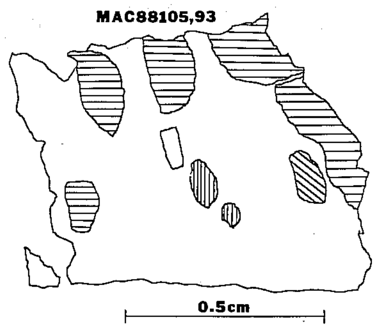


FIG. 5. Map of thin section MAC88105,93. See Fig. 2 for key to shading.

TABLE 2: Whole-rock compositions of MAC88105 samples.

SAMPLE No. Weight (mg)	,67 2.7	,69 124.6	,72 60.1	MAC88104/5 BULK*
TiO_2 (wt%)	0.41	0.25	0.22	0.23
Al_2O_3	32.9	27.5	27.9	28.0
FeO	2.94	3.90	3.80	4.34
MnO	0.047	0.058	0.056	0.064
MgO	5.7	3.2	4.6	3.50
CaO	17.7	17.2	18.5	16.5
Na_2O	0.327	0.316	0.376	0.33
K_2O	nd	0.022	0.024	0.03
MG#	78	59	68	59
Sc (ppm)	5.8	7.9	7.6	8.88
V	37	17	21	
Cr	700	490	550	653
Co	7.3	11.2	11.3	15.3
Ni	nd	110	120	160
Sr	nd	130	120	145
Ba	nd	31	41	32
La	3.8	1.92	2.48	2.57
Ce	9.0	5.7	6.6	6.74
Nd	nd	3.2	3.4	
Sm	0.271	0.88	1.12	1.22
Eu	1.00	0.80	0.82	0.80
Tb	nd	0.23	0.28	0.26
Dy	nd	1.4	1.7	
Yb	0.34	0.75	1.03	1.03
Lu	0.069	0.113	0.145	0.15
Hf	nd	0.65	0.87	0.88
Ta	nd	0.10	0.12	0.11
Th	nd	0.30	0.44	0.41
U	nd	nd	nd	0.10
Ir (ppb)	nd	9	10	7.9
Au	(51)	3	4	1.7

nd = not detected;

* = data from WARREN *et al.* (1990); LINDSTROM *et al.* (1990); KOROTEV *et al.* (1990); KOEBERL *et al.* (1990); PALME *et al.* (1990).

Drs. J.C. Laul and J.S. Schmitt (Battelle Northwest Labs., Richland, WA - pers. comm) analyzed two samples, MAC88104,16 (72.1 mg) and MAC88105,41 (77.0 mg) for long-lived radionuclides and obtained: Zn = 12 ppm; Cs = 0.066 ppm; Gd = 1.21 ppm; and Tm 0.15 ppm, in addition to other elements reported above.

As stated earlier, we received one plagioclase-rich sample with adhering matrix (,67; corresponding thin section = ,96), and two samples originally identified by the JSC Curatorial Staff as being of impact melt plus matrix (,69, corresponding thin section = ,92; and ,72, corresponding thin section = ,94). However, as noted in the petrography and mineral chemistry sections, sample ,72 is of a granulite plus breccia matrix.

We extracted the matrix-free gabbroic anorthosite clast from ,67, which allowed us to make a probe mount, but only send 2.7 mg for INA (Table 2). However, 51 ppb Au is present in ,67, suggesting substantial meteorite or terrestrial contamination. As no Ir was detected, it looks suspiciously like terrestrial contamination. The major elements are dominated by Al_2O_3 (32.9 wt%) and CaO (17.7 wt%) with subordinate amounts of FeO (2.94 wt%) and MgO (5.7 wt%) (MG# = 78; Table 2). Due to the small sample size, the accuracy of analyses for a number of the elements was such that they have unacceptably large errors associated with them. This is witnessed in the REE pattern for ,67, represented by a dashed line (Fig. 6). The LREE pattern is well defined and delineates a LREE enrichment [$(La/Sm)_N = 8.7$], but the HREEs are present in low abundances. Because Tb and Dy were below their detection limits, we have extrapolated from Yb to Sm in order to define the apparently large positive Eu anomaly [$(Eu/Eu^*)_N \sim 10$]. This pattern demonstrates the predominance of plagioclase in the bulk rock sample, but with only 2.7 mg analyzed by INA, it is likely that this analysis does not represent a true whole-rock composition. Compatible element abundances are low (Table 2), again demonstrating the predominance of plagioclase in the sample. The high field strength (HFS: Hf, Ta, Th, U) and LIL (Sr, Ba, Rb, Cs) elements were not detected.

The two other clasts (,69 and ,72) exhibit similar compositions, even though one is of an impact-melt and one is of a granulite. The major elements are dominated by Al_2O_3 (27.5 and 27.9 wt%, respectively) and CaO (17.2 and 18.5 wt%, respectively). The REE profiles are also similar, both being slightly LREE enriched (Fig. 6; [$(La/Lu)_N = 1.75$ for ,69 and 1.76 for ,72] with positive Eu anomalies [$(Eu/Eu^*)_N = 2.2$ for ,69 and 1.8 for ,72]. Generally, ,72 contains higher overall REE abundances (Fig. 6). The similarity between these two samples is also seen in the compatible HFS and remaining LIL elements (Table 2). However, these two clasts have distinct MG#s: granulite plus matrix clast ,72 contains a higher bulk rock MG# than impact melt ,69 (68 vs. 59), and we suggest that this may be due to the presence of granulitic material in this clast. The extracted gabbroic anorthosite clast ,67 contains the highest MG# (78). Substantial amounts

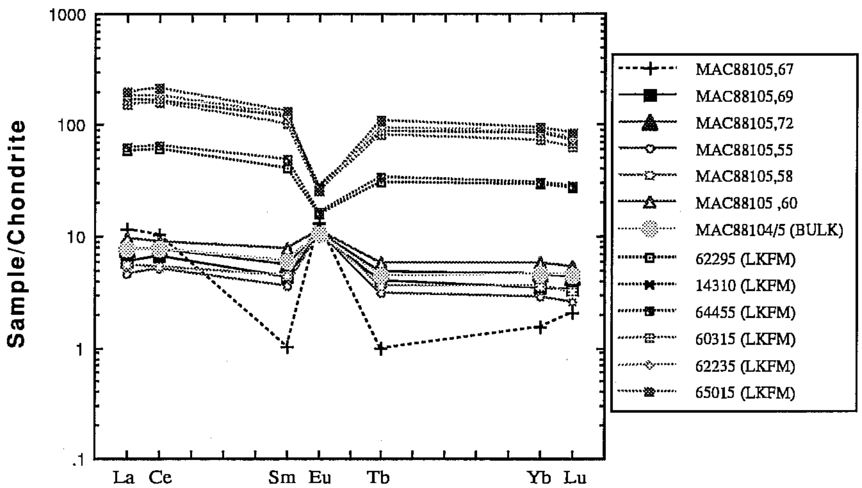


FIG. 6. Chondrite-normalized REE patterns for MAC88105,67, ,69, and ,72. Also shown is the REE profile for the bulk composition of MAC88104/5. Data from LINDSTROM et al. (1990), KOROTEV et al. (1990), WARREN et al. (1990), KOEBERL et al. (1990), and PALME et al. (1990). 62295 LKFM data from WÄNKE et al. (1976) and VANIMAN and PAPIKE (1980). Clast data from MAC88105,55, ,58, and ,60 from LINDSTROM et al. (1990).

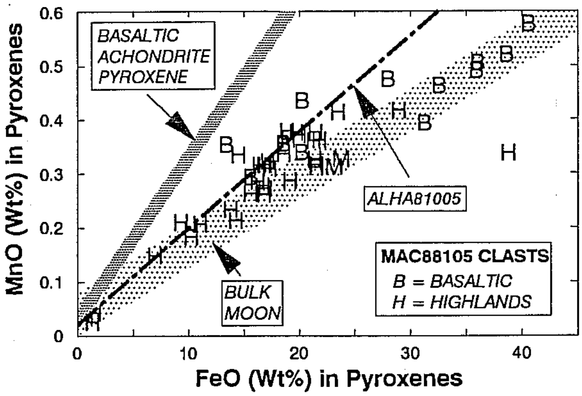


FIG. 7. Fe vs. Mn in pyroxenes demonstrating the lunar connection for lunar highland meteorite MAC88104/5.

of Ir and Au were found in both ,69 and ,72 (Ir = 9 and 10 ppb; Au = 3 and 4 ppb, respectively; Table 2), demonstrating the presence of a meteorite component in these breccias.

DISCUSSION

The mineral and bulk chemistry can be used to indicate a lunar origin for MAC88104/5. The Fe and Mn contents of pyroxenes have been previously used to demonstrate the lunar origin of other meteorites (SIMON et al., 1983; WARREN and KALLEMEYN, 1989; KURAT and BRANDSTÄTTER, 1983). The Fe/Mn ratios of MAC88105 basaltic, highland, and matrix pyroxenes are similar to those of lunar pyroxenes and lunar meteorite ALHA81005 (Fig. 7). Furthermore, MAC88105 pyroxenes have higher Fe/Mn ratios than pyroxenes from basaltic achondrites (Fig. 7). This evidence

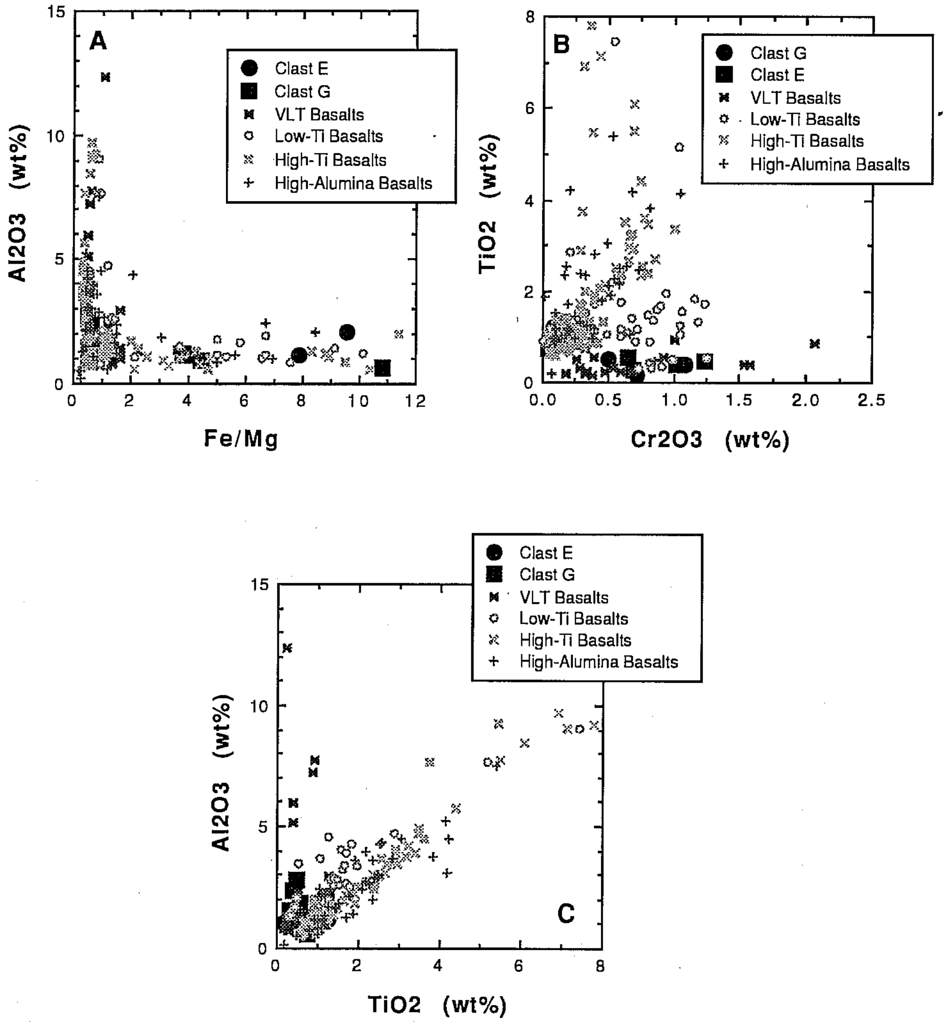


FIG. 8. Pyroxene compositions from the basaltic clasts (E and G) in MAC88105,84 compared with those from mare basalts. Mare basalt pyroxene data from: *High-Ti basalts* = BEATY and ALBEE (1978); PAPIKE et al. (1974); DYMEK et al. (1975); WARNER et al. (1975); *Low-Ti basalts* = DUNGAN and BROWN (1977); BALDRIDGE et al. (1979); BEATY et al. (1979); VETTER et al. (1988); *VLT basalts* = VANIMAN and PAPIKE (1977); COISH and TAYLOR (1978); *High-Alumina basalts* = ALBEE et al. (1972); BENCE et al. (1972); KURAT et al. (1976); LONGHI et al. (1972); RIDLEY (1975).

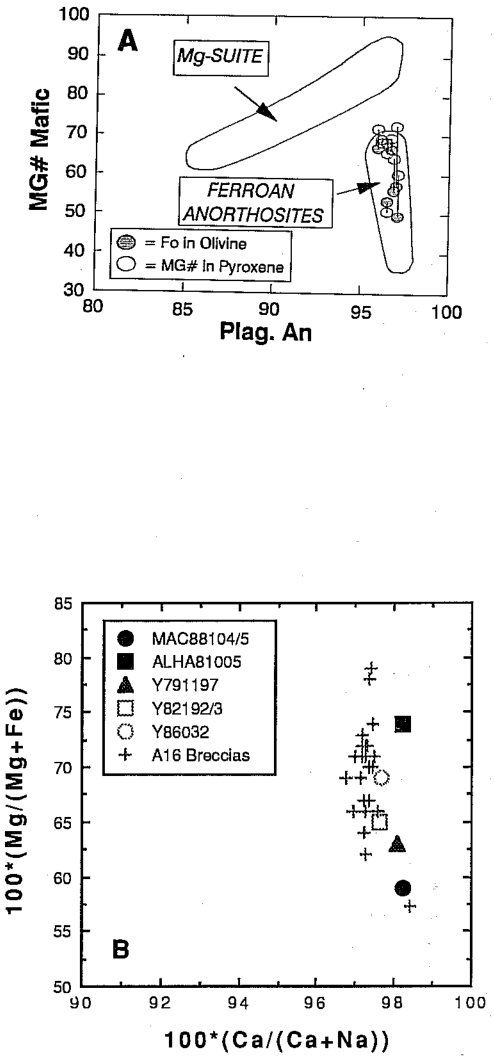


FIG. 9. (a) MG# in the mafic phase vs. the An content of the coexisting plagioclase for highland clasts in MAC88104/5; (b) MG# vs. 100*Ca/(Ca + Na) for lunar highland meteorites and Apollo 16 regolith and feldspathic breccia bulk compositions. Data from KOROTEV et al. (1990), WARREN et al. (1990), KOEBERL et al. (1989, 1990), PALME et al. (1983, 1990), WÄNKE et al. (1973), OSTERTAG et al. (1986), LINDSTROM et al. (1977, 1985, 1990), Various authors, Abstracts of the 11th Symposium on Antarctic Meteorites, NIPR (1986), BISCHOFF et al. (1987). Apollo 16 breccia data from WÄNKE et al. (1973); LINDSTROM et al. (1977); LINDSTROM and SALPAS (1981, 1983); JERDE et al. (1987, 1990); MARVIN et al. (1987); MCKAY et al. (1986).

certainly supports a lunar origin. Also, pyroxenes from the highlands clasts generally range from pigeonite to augite with little Fe-enrichment, whereas pyroxenes from the basaltic clasts exhibit more Fe-enrichment.

The origin of the basaltic clasts in MAC88105,84 can be evaluated by using the pyroxene composition and petrography. The presence of ilmenite in the "larger" basalt clast suggests that a VLT composition is unlikely, although such basalts can contain mesostasis ilmenite (VANIMAN and PAPIKE, 1977) and the presence of ilmenite (if <5%) does not negate a VLT basalt classification. The low MgO contents of this ilmenite (0.4–0.5 wt%) suggest that it is of late-stage mesostasis origin. The pyroxenes in both clasts exhibit a marked Fe enrichment from core-to-rim with little change in Ti contents (Fig. 8a). On the basis of Fe/Mg and Al_2O_3 variations, the basaltic clasts in MAC88105 are similar to high-Ti, high-alumina, and low-Ti mare basalts (Fig. 8a). However, Cr_2O_3 and TiO_2 variations in the pyroxenes from these basaltic clasts suggest an affinity with the VLT basalts (Fig. 8b). The Al_2O_3/TiO_2 variations demonstrate that they were not derived from Apollo-17–type high-Ti basalts flows as these possess a relatively constant Al/Ti ratio (Fig. 8c). The range in pyroxene Al/Ti ratio is similar to that observed in the Apollo 14 high-alumina basalts (SHERVAIS et al., 1985; NEAL et al., 1988) or low-Ti basalts (e.g., PAPIKE et al., 1976). On the basis of pyroxene data, these basaltic clasts may have an affinity with low-Ti (including high-alumina) or VLT mare basalts, but not with the high-Ti variants. The small sample size of these basalt clasts precludes any more definitive conclusions, although the low Fo content of olivine in the basalt clast E (Fo_{6-9}), coupled with the presence of SiO_2 and more evolved plagioclase compositions (An_{90-94} vs. An_{95-98}), suggests this clast is predominantly composed of mesostasis phases.

The composition of the glass beads in these MAC88104/5 thin sections can be estimated by diffuse beam microprobe analysis. In order to test the pristinity of such lunar glasses, we applied two chemical criteria defined by DELANO and LIVI (1981) and DELANO (1986). If these glasses were pristine, a single glass bead should be homogeneous: some appear to be, but others definitely are not. Also, pristine lunar magmatic glasses have Mg/Al weight ratios which are >1.5; the 88105,84 glass beads possess Mg/Al weight ratios < 0.7, overlapping with mare soils. Furthermore, the analyzed matrix glass overlaps the high-Al end of the 88105,84 glasses. Clearly, these glasses are of impact origin. FeNi metal which forms a partial halo around the glass bead (number 2; Fig. 3) in Fig. 2g contains up to 10 wt% Ni and up to 2.5 wt% Co, compositions which are more like eucrites than lunar metal, although near that of some Apollo 15 basalts (TAYLOR, 1990).

We have plotted average mineral compositions from the highlands clasts on a diagram of plagioclase An content against MG# in the mafic phase (Fig. 9a). All clasts that we analyzed fall within the ferroan anorthosite field and contain somewhat more evolved mafic phases than similar clasts in lunar meteorite ALHA81005 (WARREN et al., 1983; GOODRICH et al., 1984). Olivine is more Fe rich than pyroxene, as expected from Fe-Mg partitioning between these two coexisting phases. This relationship suggests that the granulite clasts, the gabbroic anorthosite, and impact melt were derived from a FAN source rock.

The ferroan nature of these highland lunar meteorites (except ALHA81005) is highlighted by comparison of the bulk composition of clasts (data from LINDSTROM et al., 1990; this study; TAYLOR, 1991) with the *bulk* composition of the lunar meteorites on a MG# vs. Ca/(Ca + Na) plot (Fig. 9b). The bulk composition of MAC88104/5 was calculated from analyses reported by LINDSTROM et al. (1990), KOROTEV et al. (1990), WARREN et al. (1990), KOEBERL et al. (1990), and PALME et al. (1990). All lunar meteorites have low MG#s (between 55 and 75), but high Ca/(Ca + Na) ratios. MAC88104/5 has a lower MG# than most of the Apollo 16 breccias (Fig. 9b). The lunar meteorites have similar MG#s to the Apollo 16 regolith and feldspathic breccias, but slightly higher Ca/(Ca + Na) ratios.

MAC88104/5 contains 28 wt% Al_2O_3 (Table 1). WARREN (1990) pointed out that a lunar sample containing 28 wt% Al_2O_3 is consistent with crustal formation from a magma ocean by plagioclase flotation. The mineral compositions of the highland clasts define them as members of the FAN suite. That MAC88104/5 was derived from a ferroan anorthosite terrain with little contribution from other lunar lithologies is witnessed by the similarity of the REE profiles of the impact melts, clasts, and the bulk meteorite (Fig. 6). The only exception is clast ,67 which was extracted from matrix material and is plagioclase-rich and may not be representative of a whole-rock signature.

Provenance of MAC88104/5 and Other Lunar Meteorites

The mineralogy of the lithic clasts found in this new lunar meteorite indicates derivation from ferroan anorthosite suite of highland rocks, although minor basaltic clasts are also present. The trace element geochemistry of the meteorite matrix also demonstrates a heavy plagioclase influence, characteristic of lunar highlands rocks. The incompatible element–poor nature of the impact melts and bulk meteorite MAC88104/5, coupled with the FAN suite affinity of contained granulite clasts, indicates little influence from KREEP and other lunar lithologies. However, TAYLOR (1991) has stressed the importance of KREEP in the formation of MAC88104/5 impact melt clasts. The range in major element compositions of the clasts reported by TAYLOR (1991) and their similarity to Apollo 16 KREEPy impact melts compositions demonstrated the heterogeneity of this component in the lunar highlands, but its importance is that it is derived from the lower crust during basin-forming events (RYDER and WOOD, 1977; SPUDIS and DAVIS, 1986).

TABLE 3: Comparison of the impact melt compositions from our study with the Al-rich composition reported by TAYLOR (1991) (denoted by @) and the Group 3 Apollo 16 melt reported by MCKINLEY *et al.* (1984) (denoted by *).

SAMPLE No. Weight (mg)	,69 124.6	,72 60.1	64504,15* "Group 3"	88105@ Al-rich	88105@ Granulites
TiO_2 (wt%)	0.25	0.22	0.3	0.23	0.12
Al_2O_3	27.5	27.9	28.4	28.0	30.4
FeO	3.90	3.80	4.1	3.8	2.2
MnO	0.058	0.056	0.057	0.06	0.04
MgO	3.2	4.6	4.0	3.2	1.8
CaO	17.2	18.5	16.3	15.6	17.8
Na_2O	0.316	0.376	0.468	0.28	0.30
K_2O	0.022	0.024	0.065	0.04	0.04
MG#	59	68	64	60	59
Sc (ppm)	7.9	7.6	8.0		
V	17	21	22		
Cr	490	550	561	684	411
Co	11.2	11.3	14		
Ni	110	120	170		
Sr	130	120			
Ba	31	41	90		
La	1.92	2.48	7.4		
Ce	5.7	6.6	17		
Nd	3.2	3.4	12		
Sm	0.88	1.12	3.6		
Eu	0.80	0.82	1.01		
Tb	0.23	0.28	0.74		
Dy	1.4	1.7	4.3		
Yb	0.75	1.03	2.3		
Lu	0.113	0.145	0.34		
Hf	0.65	0.87	2.5		
Ta	0.10	0.12	0.4		
Th	0.30	0.44	1.2		
U	nd	nd	0.3		
Ir (ppb)	9	10			
Au	3	4			

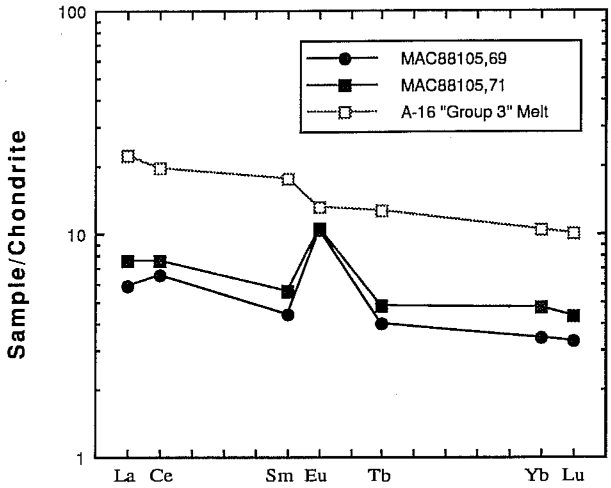


FIG. 10. Comparison of the impact melt clasts MAC88105,69 and ,72 with the Apollo 16 "Group 3" melt (64504) reported by MCKINLEY et al. (1984). Although these are similar in major elements (Table 2), there are significant differences in REEs and other incompatible element contents.

In our study we have examined two impact melts by INA (,69 and ,72; Table 2). Generally, these clasts have the same composition as the bulk MAC88104/5 lunar meteorite (e.g., Fig. 6 and Table 2), but we see no evidence for the influence of KREEP in our samples. For example, the REE are low and a positive Eu anomaly is present in our samples and in the clasts of LINDSTROM et al. (1990), rather than a negative anomaly as in KREEP (WÄNKE et al., 1976; VANIMAN and PAPIKE, 1980). Potassium contents are also low in the MAC88105 impact melts from our study and those of LINDSTROM et al. (1990; $\ll$0.1 wt%) relative to LKFM and two of the four impact melts reported by TAYLOR (1991). On the basis of major element data, our two impact melt clasts (,69 and ,72) are similar to two of the impact melt types reported by TAYLOR (1991). This author noted the similarity of his Al-rich impact melt to a typical Apollo 16 "Group 3" melt reported by MCKINLEY et al. (1984; Table 3). However, the REE profiles are grossly different (Fig. 10), suggesting that the KREEP contribution to breccia MAC88104/5 was minimal at best.

The plagioclase-rich and brecciated nature of MAC88104/5, as well as lunar meteorites Y791197, ALHA81005, Y82192/3, and Y86032, indicate derivation from a highlands region; and the ferroan nature of these meteorites (except ALHA81005) suggests a site dominated by ancient lunar crust. As such, we have compared the bulk composition of these lunar meteorites with feldspathic and regolith breccias from the only lunar anorthositic highland site visited during the Apollo program—Apollo 16. The feldspathic nature of the lunar meteorites is highlighted in Fig. 11a. The bulk composition of the lunar meteorites falls within the field defined by Apollo 16 regolith and feldspathic breccias. All lunar meteorites contain lower Eu abundances than the Apollo 16 breccias, and the REE profiles of these meteorites fall at the

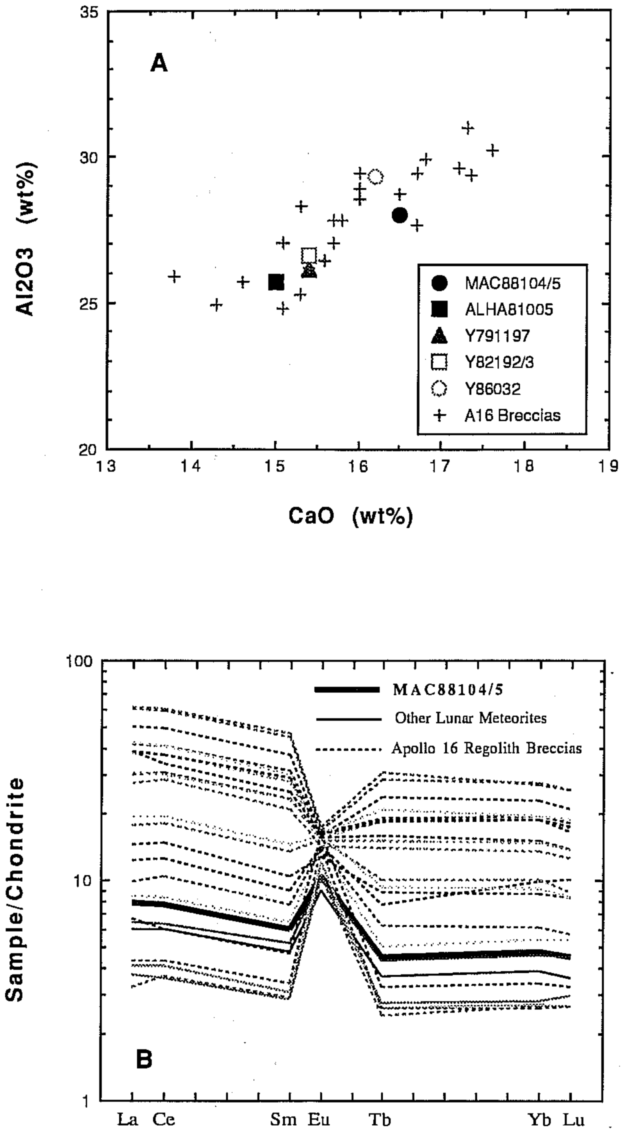


FIG. 11. Comparison of major- and trace-element bulk compositions of the Lunar meteorites with those of Apollo 16 regolith and feldspathic breccias: (a) CaO (wt%) vs. Al_2O_3 (wt%) demonstrating the feldspar-rich nature and the similar major element compositions of the lunar meteorites and the Apollo 16 breccias; (b) Chondrite-normalized REE profiles demonstrate the REE-poor nature of the lunar meteorites relative to the majority of Apollo 16 breccias, which in turn indicates a lack of a LKFM component in the lunar meteorites. Data sources as in Fig. 9b.

lower end of the Apollo 16 breccia array (Fig. 11b). The high MG# of ,67 may be a result of unrepresentative sampling or the mixing in of a minor high-Mg component. Although no firm conclusions can be made on the basis of analyzing 2.7 mg, the range of mineral compositions in the gabbroic anorthosite (,67/,96) suggests disequilibrium in this clast, may be because of the impact induced mixing of a component with higher Mg contents than the dominant FAN-suite lithologies.

Generally, the Apollo 16 breccias are enriched in the incompatible trace elements relative to the lunar meteorites. Therefore, it is difficult to envisage Apollo 16 as being the site of origin for these new lunar samples. Rather, a highland site more ferroan, REE-poor, and KREEP-poor is required. We suggest that at least MAC88104/5 and maybe all lunar meteorites of highland affinities, were originally derived from ancient ferroan anorthosite lunar crust. At least two impacts were responsible for the formation of the brecciated lunar meteorites and then their expulsion from the Moon.

SUMMARY

Mineral chemistry supports macroscopic observations and oxygen isotope analyses in defining a lunar origin for meteorite MAC88104/5. This anorthositic breccia contains highlands clasts derived from the ferroan anorthosite suite, as well as clasts of basaltic affinities which may be VLT or low-Ti/high-alumina in bulk composition. Glass beads in the breccia are of impact origin and mirror the composition of the impact melts, bulk breccia, and clast compositions. The origin of the metal/sulfide halo around bead 4 in MAC88105,84 (Fig. 3) remains obscure.

The general differences between all highland lunar meteorites and Apollo 16 regolith breccias suggests that this site is not a good candidate for the origin of the brecciated lunar meteorites. Rather, a more ferroan highland locality is required for these meteorites, except for ALHA81005. On the basis of the above data, we conclude that MAC88104/5 was derived from an area of the Moon comprised primarily of ferroan anorthosite suite rocks formed from a lunar magma ocean, with a minor mare component. Compositional similarities between MAC88104/5 and all brecciated lunar meteorites (except ALHA81005) suggest all may have been derived from a similar site. The incompatible trace-element poor nature of these lunar meteorites, coupled with the presence of a positive Eu anomaly, suggests that there was little KREEPy influence within the area from which these meteorites were derived.

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REFERENCES

Abstracts of the 11th Symposium on Antarctic Meteorites (1986) NIPR, Tokyo.

ALBEE A. L., CHODOS A. A., GANCARZ A. J., HAINES E. L., PAPANASTASSIOU D. A., RAY L., TERA F., WASSERBURG G. J., and WEN T. (1972) Mineralogy, petrology, and chemistry of a Luna 16 basaltic fragment, sample B-1. *Earth Planet. Sci. Lett.* **13,** 353–367.

BALDRIDGE W. S., BEATY D. W., HILL S. M. R., and ALBEE A. L. (1979) The petrology of the Apollo 12 pigeonite basalt suite. *Proc. 10th Lunar Planet. Sci. Conf.,* 141–179.

BEATY D. W. and ALBEE A. L. (1978) Comparative petrology and possible genetic relations among the Apollo 11 basalts. *Proc. 9th Lunar Planet. Sci. Conf.,* 359–463.

BEATY D. W., HILL S. M. R., ALBEE A. L., and BALDRIDGE W. S. (1979) Apollo 12 feldspathic basalts 12031, 12038, and 12072: Petrology, comparison, and interpretations. *Proc. 10th Lunar Planet. Sci. Conf.,* 115–139.

BENCE A. E., HOLZWARTH W., and PAPIKE J. J. (1972) Petrology of basaltic and monomineralic soil fragments from the Sea of Fertility. *Earth Planet. Sci. Lett.* **13,** 299–311.

BISCHOFF A., PALME H., WEBER H. W., STÖFFLER D., BRAUN O., 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. *Mem. NIPR* (Spec. Issue) **46,** 21–42.

CLAYTON R. (1989) *Antarctic Meteorite Newsletter* **12,** No. 3, p. 21.

COISH R. A. and TAYLOR L. A. (1978) Mineralogy and petrology of basaltic fragments from the Luna 24 drill core. In *Mare Crisium: The View from Luna 24* (eds. R. B. MERRILL and J. J. PAPIKE), pp. 403–418. Pergamon.

DELANEY J. S. and SUTTON S. R. (1990) Petrography of meteoritic VLT basalt breccia (87521) from Elephant Moraine, Antarctica (abstr.). *Lunar Planet. Sci. XXI,* 274–275.

DELANO J. W. (1986) Pristine lunar volcanic glasses: Criteria, data, and implications. *Proc. 16th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **91,** D201–D213.

DELANO J. W. and LIVI K. (1981) Lunar volcanic glasses and their constraints on mare petrogenesis. *Geochim. Cosmochim. Acta* **45,** 2137–2149.

DUNGAN M. A. and BROWN R. W. (1977) The petrology of the Apollo 12 ilmenite basalt suite. *Proc. 8th Lunar Sci. Conf.,* 1339–1381.

DYMEK R. F., ALBEE A. L., and CHODOS A. A. (1975) Comparative mineralogy and petrology of Apollo 17 mare basalts: Samples 70215, 71055, and 75055. *Proc. 6th Lunar Sci. Conf.,* 49–77.

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.

HUGHES S. S., DELANO J. W., and SCHMITT R. A. (1989) Petrogenetic modeling of 74220 high-Ti orange volcanic glasses and the Apollo 11 and 17 high-Ti mare basalts. *Proc. 19th Lunar Planet. Sci. Conf.,* 175–188.

JERDE E. A., WARREN P. H., MORRIS R. V., HEIKEN G. H., and VANIMAN D. T. (1987) A potpourri of regolith breccia: "New" samples from the Apollo 14, 16, and 17 landing sites. *Proc. 17th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **92,** E526–E536.

JERDE E. A., MORRIS R. V., and WARREN P. H. (1990) In quest of lunar regolith breccias of exotic provenance: A uniquely anorthositic component from the Fra Mauro (Apollo 14) highlands. *Earth Planet. Sci. Lett.* **98,** 90–108.

KOEBERL C., WARREN P. H., LINDSTROM M. M., SPETTEL B., and FUKUOKO T. (1989) Preliminary examination of the Yamato-86032 lunar meteorite, II. Major and trace element chemistry. *Proc. NIPR Symp. Antarctic Met.* **2,** 15–24.

KOEBERL C., KURAT G., and BRANDSTÄTTER F. (1990) MAC88105—A new meteorite from the lunar highlands: Preliminary mineralogical, petrological, and geochemical studies (abstr.). *Lunar Planet. Sci. XXI,* 645–646.

KOROTEV R. L., JOLLIFF B. L., and HASKIN L. A. (1990) Preliminary report of geochemical study of lunar meteorites MAC88104 and MAC88105 (abstr.). *Lunar Planet. Sci. XXI,* 666–667.

KURAT G. and BRANDSTÄTTER F. (1983) Meteorite ALHA81005: Petrology of a new lunar highland sample. *Geophys. Res. Lett.* **10,** 795–798.

KURAT G., KRACHER A., KEIL K., WARNER R., and PRINZ M. (1976) Composition and origin of Luna 16 aluminous mare basalts. *Proc. 7th Lunar Sci. Conf.,* 1301–1321.

LINDSTROM M. M. and SALPAS P. A. (1981) Geochemical studies of rocks from North Ray crater, Apollo 16. *Proc. 12th Lunar Planet. Sci. Conf.,* 305–322.

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., NAVA D. F., LINDSTROM D. J., WINZER S. R., LUM R. K. L., SCHUMANN P. J., SCHUMANN S., and PHILPOTTS J. A. (1977) Geochemical studies of the White Breccia Boulders at North Ray crater, Descartes region of the lunar highlands. *Proc. 8th Lunar Sci. Conf.,* 2137–2151.

LINDSTROM M. M., LINDSTROM D. J., KOROTEV R. L., and HASKIN L. A. (1985) Lunar meteorites Yamato 791197 and ALHA81005: The same yet different (abstr.). *Papers Presented to the 10th Symposium on Antarctic Meteorites, Tokyo.* pp. 119–121. NIPR.

LINDSTROM M. M., LINDSTROM D. J., KOROTEV R. L., and HASKIN L. A. (1986) Lunar meteorite Yamato-791197: A polymict anorthositic norite breccia. *Mem. NIPR* (Spec. Issue) **41,** 58–75.

LINDSTROM M. M., MARTINEZ R. R., and MITTLEFELHDT D. W. (1990) Geochemistry of lunar meteorites MAC88104 and MAC88105 (abstr.). *Lunar Planet. Sci. XXI,* 704–705.

LINDSTROM M. M., SCHWARCZ C., SCORE R., and MASON B. (1991) MacAlpine Hills 88104 and 88105 lunar highland meteorites: General description and consortium overview. *Geochim. Cosmochim. Acta* **55,** 2999–3007 (this issue).

LONGHI J., WALKER D., and HAYS J. F. (1972) Petrography and crystallization history of basalts 14310 and 14072. *Proc. 3rd Lunar Sci. Conf.,* 131–139.

MARVIN U. B. (1983) The discovery and initial characterization of Allan Hills 81005: The first lunar meteorite. *Geophys. Res. Lett.* **10,** 775–778.

MARVIN U. B., LINDSTROM M. M., BERNATOWICZ T. J., PODOSEK F. A., and SUGIURA N. (1987) The composition and history of breccia 67015 from North Ray crater. *Proc. 17th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **92,** E471–E490.

MCKAY D. S., BOGARD D. D., MORRIS R. V., KOROTEV R. L., JOHNSON P., and WENTWORTH S. J. (1986) Apollo 16 regolith breccias: Characterization and evidence for early formation in the mega-regolith. *Proc. 16th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **91,** D277–D304.

MCKINLEY J. P., TAYLOR G. J., KEIL K., MA M., and SCHMITT R. A. (1984) Apollo 16: Impact melt sheets, contrasting nature of the Cayley Plains and Descartes Mountains, and geologic history. *Proc. 14th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **89,** B513–B524.

NEAL C. R., TAYLOR L. A., and LINDSTROM M. M. (1988) Apollo 14 mare basalt petrogenesis: Assimilation of KREEP-like components by a fractionating magma. *Proc. 18th Lunar Planet. Sci. Conf.,* 139–153.

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. *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., BURGHELE A., DREIBUS G., WECKWERTH G., WÄNKE H., JOCHUM J. P., WEBER H., BISCHOFF A., and STÖFFLER D. (1990) Big MAC, little MAC, and the composition of the lunar crust (abstr.). *Lunar Planet. Sci. XXI,* 930–931.

PAPIKE J. J., BENCE A. E., and LINDSLEY D. H. (1974) Mare basalts from the Taurus-Littrow region of the Moon. *Proc. 5th Lunar Sci. Conf.,* 471–504.

PAPIKE J. J., HODGES F. N., BENCE A. E., CAMERON M., and RHODES J. M. (1976) Mare basalts: Crystal chemistry, mineralogy, and petrology. *Rev. Geophys. Space Phys.* **14,** 475–540.

RIDLEY W. I. (1975) On high-alumina basalts. *Proc. 6th Lunar Sci. Conf.,* 131–145.

RYDER G. and WOOD J. A. (1977) Serenitatis and Imbrium impact melts: Implications for large-scale layering in the lunar crust. *Proc. 8th Lunar Sci. Conf.,* 655–668.

SCORE R. (1989) *Antarctic Meteorite Newsletter* **12,** No. 3, p. 21.

SCORE R., LINDSTROM M. M., and MASON B. (1989) Collection, classification, and description of MAC88104 and MAC88105—two fragments of a lunar meteorite. Supplemental Abstract at 52nd Meteoritical Society Meeting, Vienna.

SHERVAIS J. W., TAYLOR L. A., and LINDSTROM M. M. (1985) Apollo 14 mare basalts: Petrology and geochemistry of clasts from consortium breccia 1321. *Proc. 15th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **90,** C375–C395.

SHERVAIS J. W., TAYLOR L. A., and LINDSTROM M. M. (1988) Olivine vitrophyres: A nonpristine high-Mg component in lunar breccia 14321. *Proc. 18th Lunar Planet. Sci. Conf.*, 45–58.

SIMON S. B., PAPIKE J. J., and SHEARER C. K. (1983) Petrology of ALHA81005, the first lunar meteorite. *Geophys. Res. Lett.* **10,** 787–790.

SPUDIS P. D. and DAVIS P. A. (1986) A chemical and petrological model for the lunar crust and implications for lunar crustal origin. *Proc. 17th Lunar Planet. Sci. Conf.; J. Geophys. Res.* **91,** E84–E90.

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

TAYLOR L. A. (1990) Rocks and minerals in the regolith of the Moon: Resources for a lunar base. In *Lunar Source Book*, pp. 29–47. Cambridge University Press.

VANIMAN D. T. and PAPIKE J. J. (1977) Very low-Ti (VLT) basalts: A new mare rock type from the Apollo 17 drill core. *Proc. 8th Lunar Sci. Conf.*, 1443–1471.

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

VETTER S. K., SHERVAIS J. W., and LINDSTROM M. M. (1988) Petrology and geochemistry of olivine-normative and quartz-normative basalts from regolith breccia 15498: New diversity in Apollo 15 mare basalts. *Proc. 18th Lunar Planet. Sci. Conf.*, 255–272.

WÄNKE H., PALME H., KRUSE H., BADDENHAUSEN H., CENDALES M., DREIBUS G., HOFMEISTER H., JAGOUTZ E., PALME C., SPETTEL B., and THACKER R. (1976) Chemistry of lunar highland rocks: A refined evaluation of the composition of the primary matter. *Proc. 7th Lunar Sci. Conf.*, 3479–3499.

WÄNKE H., BADDENHAUSEN H., DREIBUS G., JAGOUTZ E., KRUSE H., PALME H., SPETTEL B., and TESCHKE F. (1973) Multielement analyses of Apollo 15, 16, and 17 samples and the bulk composition of the Moon. *Proc. 4th Lunar Sci. Conf.*, 1461–1481.

WARNER R. D., KEIL K., PRINZ M., LAUL J. C., MURALI A. V., and SCHMITT R. A. (1975) Mineralogy, petrology, and chemistry of mare basalts from Apollo 17 rake samples. *Proc. 6th Lunar Sci. Conf.*, 193–220.

WARREN P. H. (1985) The magma ocean concept and lunar evolution. *Ann. Rev. Earth Planet. Sci.* **13,** 201–240.

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. (1987) Geochemistry of lunar meteorite Yamato-86032: Comparison with Yamato-791197, ALHA81005, and other lunar samples. *Mem. NIPR* (Spec. Issue) **6,** 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,** 3323–3330.

WARREN P. H., TAYLOR G. J., and KEIL K. (1983) Regolith breccia Allan Hills 81005: Evidence of lunar origin, and petrography of pristine and non-pristine clasts. *Geophys. Res. Lett.* **10,** 779–782.

WARREN P. H., KALLEMEYN G. W., and JERDE E. A. (1990) Compositional-petrographic investigation of two newly-acquired Moon rocks (abstr.). *Lunar Planet. Sci. XXI,* 1297–1298.

YANAI K. (1990) Anorthositic gabbro: Cumulate meteorite from antarctica. *Lunar Planet. Sci. XXI* 1365–1366.