LUNAR METEORITE YAMATO-791197: A POLYMICT ANORTHOSITIC NORITE BRECCIA

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Abstract: The lunar origin of Antarctic meteorite Yamato-791197 is confirmed by geochemical and petrologic studies of four subsamples of split 89. The meteorite has a bulk composition of ferroan anorthositic norite with very low incompatible element concentrations. It is a breccia containing clasts of igneous and metamorphic lunar highlands rocks, melt rocks and glasses derived from them by impact, and rare clasts of mare basalt. Y-791197 is similar in composition and clast assemblage to ALHA81005, but there are significant differences between the two meteorites in the ratio of Mg/Fe, concentrations of Sc and REE, and proportions of clast types. These differences are no greater than those observed among breccias ejected by a single lunar impact of modest size (1 km crater), so the derivation of Y-791197 and ALHA81005 from a single impact is possible. Regional differences in clast assemblages between Apollo sites are much larger, so the similarities in clast assemblage between the two meteorites support the suggestion that they originated from the same region of the Moon. We conclude that the two meteorites were ejected from the Moon by the same impact. The lunar meteorites are very similar in composition to lunar granulitic breccias and to the estimated average composition of the lunar highlands, unlike most Apollo highlands soils and breccias which are enriched in a KREEP component. The dominance of plutonic anorthositic norite precursors in the granulites and their common occurrence in the lunar meteorites suggest that abundant quantities of anorthositic norites were produced during lunar crustal evolution.

1. Introduction

The discovery that certain meteorites found in Antarctica are lunar regolith breccias is of major importance to both lunar and meteoritic science. Meteorites from the Moon are rare and none had been discovered prior to direct sampling of the Moon. Now four are known, all from the recent Antarctic collections (YANAI and KOJIMA, 1985). Also present in those collections are meteorites proposed to have come from Mars, a proposal that cannot be verified until we have more reliable data on Martian compositions. No lunar or Martian meteorites were expected because theories of cratering mechanics predicted that macroscopic objects ejected from large bodies at their escape velocities would not survive intact (MELOSH, 1983). The discovery of meteorites of undisputed lunar origin is causing adjustments to those theories (MELOSH, 1985). It is important to those modifications to know whether the four Antarctic lunar meteorites were ejected from the Moon in separate lunar events or in a single one.

The lunar meteorites are breccias from unsampled regions of the Moon and are valuable additions to the lunar samples returned by the Apollo and Luna missions. Studies of meteorite ALHA81005 demonstrated not only that the specimen was lunar, but that it probably derived from a region remote from the Apollo sites (BOGARD, ed., 1983). Typical lunar highlands material, according to the remotely sensed gamma- and X-ray data (TAYLOR, 1982) more closely resembles ALHA81005 in composition than it resembles most Apollo samples. Despite the absence of information on precisely which regions of the lunar surface the lunar meteorites came from, these meteorites extend our sampling of the Moon significantly. How much they extend it depends on how different the four meteorites are from each other in composition and population of lithic clasts and whether the four meteorites represent more than a single lunar location.

In this paper we describe the results of our geochemical and petrographic studies of Antarctic meteorite Yamato-791197. We conclude that this meteorite, despite some interesting differences in composition from ALHA81005, probably originated from the same region of the lunar regolith as did ALHA81005, and that the two meteorites were ejected from the Moon by the same impact. We show that the composition and mineralogy of lithic fragments in the two meteorites and in Apollo granulitic breccias with similar compositions (LINDSTROM and LINDSTROM, 1986) support our suggestion (KOROTEV *et al.*, 1983) that plutonic anorthositic norites are important in lunar crustal evolution.

2. Sampling and Analytical Procedures

We divided Y-791197,89 into five subsamples in an attempt to separate clasts and matrix. However the clasts were small and the matrix coherent, so we were only able to obtain subsamples enriched in the lithologies corresponding to the largest clasts. The subsamples still contain approximately 50% matrix and smaller clasts and are discussed as bulk rock samples, not as separated clasts. Subsample 89,1 is enriched in a green clast; 89,2 is enriched in a light gray melt rock; 89,3 is breccia matrix; and 89,4 is fine residue from the chipping process. The remaining 20 mg were separated for fission track (CROZAZ, 1985) and thermoluminescence (SUTTON, 1985) studies.

Subsamples 89,1–89,4 were analyzed by instrumental neutron activation analysis (INAA) using procedures similar to those of KOROTEV (1986). They were irradiated for 48 hours at a thermal neutron flux of 4×10^{13} $\text{cm}^{-2}\text{s}^{-1}$ and were radioassayed for gamma rays one week and three weeks after irradiation. Data were reduced by the TEABAGS program of LINDSTROM and KOROTEV (1982). Analytical uncertainties are tabulated as one sigma counting statistics.

Following INAA, subsamples 89,1–89,3 were mounted in epoxy and polished for study on our JEOL 733 electron microprobe. Backscattered electron imaging and energy dispersive X-ray analysis provided textural and semi-quantitative compositional information on clasts and matrix. Quantitative wavelength dispersive analyses were done on selected clasts.

3. Results: Description of Y-791197

3.1. *Bulk composition*

Table 1 lists results of INAA of our four subsamples of Y-791197,89 together with

Table 1. Element concentrations in samples of Y-791197 and comparison to ALHA81005 and various lunar compositions. Values in μg/g, except oxides in % (cg/g), and Ir and Au in ng/g.

	Y-791197							ALHA 81005	Apollo 16				Lunar crust average[5]
	89,1	89,2	89,3	89,4	unc. 1σ	mass wt'd mean	range bulk lit.[1]	mass wt'd mean[2]	rock 67215[3]	rock 67415[3]	soil NRC[4]	soil mean[4]	
SiO_2	n.a.	n.a.	n.a.	n.a.	—	n.a.	n.a.	46.5	n.a.	44.6	45.1	45.1	45.
TiO_2	n.a.	n.a.	n.a.	n.a.	—	n.a.	0.27–0.36	0.23	0.38	0.42	0.36	0.59	0.56
Al_2O_3	n.a.	n.a.	n.a.	n.a.	—	n.a.	26.0–28.9	25.1	25.8	26.1	29.0	26.8	24.6
FeO	5.98	6.06	6.27	5.99	0.06	6.09	5.73–6.84	5.46	7.1	4.78	3.93	5.38	6.6
MgO	n.a.	n.a.	n.a.	n.a.	—	n.a.	4.5 –6.5	8.8	6.0	7.86	4.35	6.00	6.8
CaO	15.0	15.1	14.9	14.8	0.3	15.0	14.5–16.0	14.9	15.5	14.8	16.4	15.6	15.8
Na_2O	0.324	0.334	0.331	0.331	0.003	0.329	0.32–0.35	0.321	0.30	0.51	0.53	0.47	0.45
K_2O	0.025	0.027	0.023	0.023	0.014	0.025	0.03–0.04	<0.04	0.011	0.05	0.07	0.15	0.075
Sc	12.87	13.78	14.02	12.82	0.13	13.43	12.5–16.5	8.81	15.2	6.71	6.7	9.4	10.
Cr	940.	933.	938.	906.	9.	935.	750 –1034	900.	860.	735.	497.	737.	680.
Co	21.6	17.1	19.4	19.2	0.2	19.7	17.0–20.5	22.5	13.5	19.9	14.	28.	15.
Ni	214.	152.	185.	193.	8–13	189.	110 –210	243.	40.	232.	133.	401.	100.
Br	0.15	0.27	0.18	0.46	0.03	0.21	n.a.	0.33	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	148.	152.	149.	141.	9–16	149.	90 –140	141.	130.	187.	190.	162.	120.
Zr	47.	47.	42.	40.	13–24	45±15	26 –43	19±12	n.a.	57.	70.	173.	63.
Ba	30.	32.	36.	38.	3–5	33.	20 –32	24.	18.	66.	66.	131.	66.
La	2.24	2.95	2.55	2.59	0.03	2.53	2.16–3.3	1.86	1.19	4.43	5.57	12.6	5.3
Ce	5.7	7.4	6.6	6.7	0.3	6.45	5.2 –9.1	4.54	3.2	11.4	14.4	32.4	12.
Nd	3.6	4.7	4.3	3.6	1.2	4.1	3.0 –5.2	2.6	2.4	6.1	n.a.	n.a.	7.4
Sm	1.11	1.44	1.25	1.24	0.02	1.24	0.99–1.56	0.866	0.72	1.82	2.58	5.93	2.0
Eu	0.750	0.791	0.770	0.762	0.012	0.766	0.72–0.72	0.702	0.73	1.09	1.23	1.21	1.0
Tb	0.26	0.33	0.29	0.30	0.02	0.29	0.22–0.32	0.19	0.20	0.42	0.52	1.13	0.41
Yb	0.97	1.17	1.08	1.03	0.02	1.05	0.96–1.33	0.69	0.77	1.66	1.90	4.22	1.4
Lu	0.143	0.174	0.159	0.155	0.003	0.156	0.14–0.19	0.106	0.125	0.24	0.26	0.62	0.21
Hf	0.85	1.03	0.93	0.93	0.03	0.92	0.73–1.1	0.63	0.78	1.56	1.67	4.3	1.4
Ta	0.103	0.128	0.107	0.108	0.009	0.110	0.08–0.16	0.079	0.09	0.30	0.29	0.53	n.a.
Ir	9.7	4.5	6.6	4.0	0.5	7.1	4.5 –8.0	7.6	1.0	3.9	n.a.	n.a.	n.a.
Au	1.8	1.4	3.4	4.2	0.4	2.4	2.1 –2.5	n.a.	n.a.	—	n.a.	n.a.	n.a.
Th	0.31	0.36	0.33	0.29	0.02	0.33	0.28–0.45	0.198	0.12	0.94	0.91	2.1	0.9
U	0.10	0.13	0.12	0.13	0.02	0.12	0.08–0.13	0.09	n.a.	0.22	0.26	0.61	0.24
mass (mg)	36.35	21.62	30.34	8.22		96.53		77.71					

n.a. = not analyzed or reported. 1) Papers presented to the 10th Symp. Antarct. Metorites (1985).
2) Korotev *et al.* (1983), with FeO and REE data normalized to standard values used in this work.
3) Lindstrom and Lindstrom (1986). 4) Korotev *et al.* (1980). 5) Taylor (1982).

their mass-weighted mean composition, the range of analyses of other bulk or matrix samples of the meteorite (FUKUOKA *et al.*, 1985; NAKAMURA *et al.*, 1985; OSTERTAG *et al.*, 1985; TAKAHASHI *et al.*, 1985; WARREN and KALLEMEYN, 1985), and compositions of similar lunar materials. Despite visible lithological differences, our four subsamples have remarkably similar compositions. Variations in abundances of most elements are small, sometimes within analytical uncertainties. Major elements and compatible trace elements show the least variation, having range factors (RF=maximum/minimum concentrations for our four subsamples) of 1.01 to 1.10. Incompatible element concentrations are more variable (RF=1.2 to 1.4), while siderophile element concentrations are most variable, (RF=1.4 to 2.2). Our results for most elements fall within or near the range of concentrations found by other investigators for bulk samples. Analyses of several larger clasts (FUKUOKA *et al.*, 1985; NAKAMURA *et al.*, 1985; WARREN and KALLEMEYN, 1985) are also quite similar to those of matrix and bulk samples, but usually fall slightly outside the range for matrix samples.

Y-791197 has the major element composition of anorthositic norite, with approximately 27% Al_2O_3, 15% CaO, 6.3% FeO, 5.5% MgO, less than 1% each of TiO_2, Na_2O and K_2O, and SiO_2 (by difference) of 45%. This composition is very similar to those of ALHA81005 and selected rocks and typical soils from Apollo 16 (Table 1). Variations in the ratio of Mg to Fe, expressed as Mg′=(mole % Mg/(Mg+Fe)), are important in studies of lunar crustal evolution. Y-791197 has an Mg′ value of 61, which is within the range of Apollo 16 samples.

The very low concentrations of Na_2O (0.33%) and K_2O (0.03%) are within the ranges of lunar highlands samples, but are lower than those of most polymict lunar samples. Na and K are incompatible elements in lunar highlands rocks, as are the trace elements Rb, Cs, Ba, Zr, Hf, Ta, Th, U and REE. In Apollo polymict breccias and soils, these elements are concentrated in a KREEP component (MEYER, 1977) which is heterogeneously distributed in lunar rocks. Incompatible trace elements concentrations in Y-791197 are only slightly higher than those in ALHA81005, and both meteorites have concentrations similar to those of Apollo 16 rocks 67215 and 67415. However, all four samples have distinctly lower incompatible element concentrations than are found in most lunar polymict breccias and soils. These variations are shown in Fig. 1, in which rare earth element (REE) concentrations are plotted normalized to those of chondritic meteorites (NAKAMURA, 1974). Figure 1a shows the mean of our four analyses of Y-791197, the range for all analyzed bulk or matrix samples, and the concentrations for three clasts. The extent of REE variation in Y-791197 is small for a polymict breccia, but might result from the limited sampling. Relative REE concentrations are similar for most matrix samples, with maximum variation a factor of 1.5. The matrix concentrations are bracketed by those of the clasts which show significant differences in slope of the light REE. Relative REE abundances for ALHA81005 (Fig. 1b) are similar to those of Y-791197, but average concentrations are slightly lower. Matrix concentrations vary by only a factor of 1.3 but clast concentrations are more variable than those in Y-791197. The similar extents of matrix variation in the two breccias suggest that sampling of Y-791197 has been adequate to characterize the bulk rock, but the more extensive variation in clasts from ALHA81005 shows that additional analyses of clasts from Y-791197 may be needed to characterize the clasts.

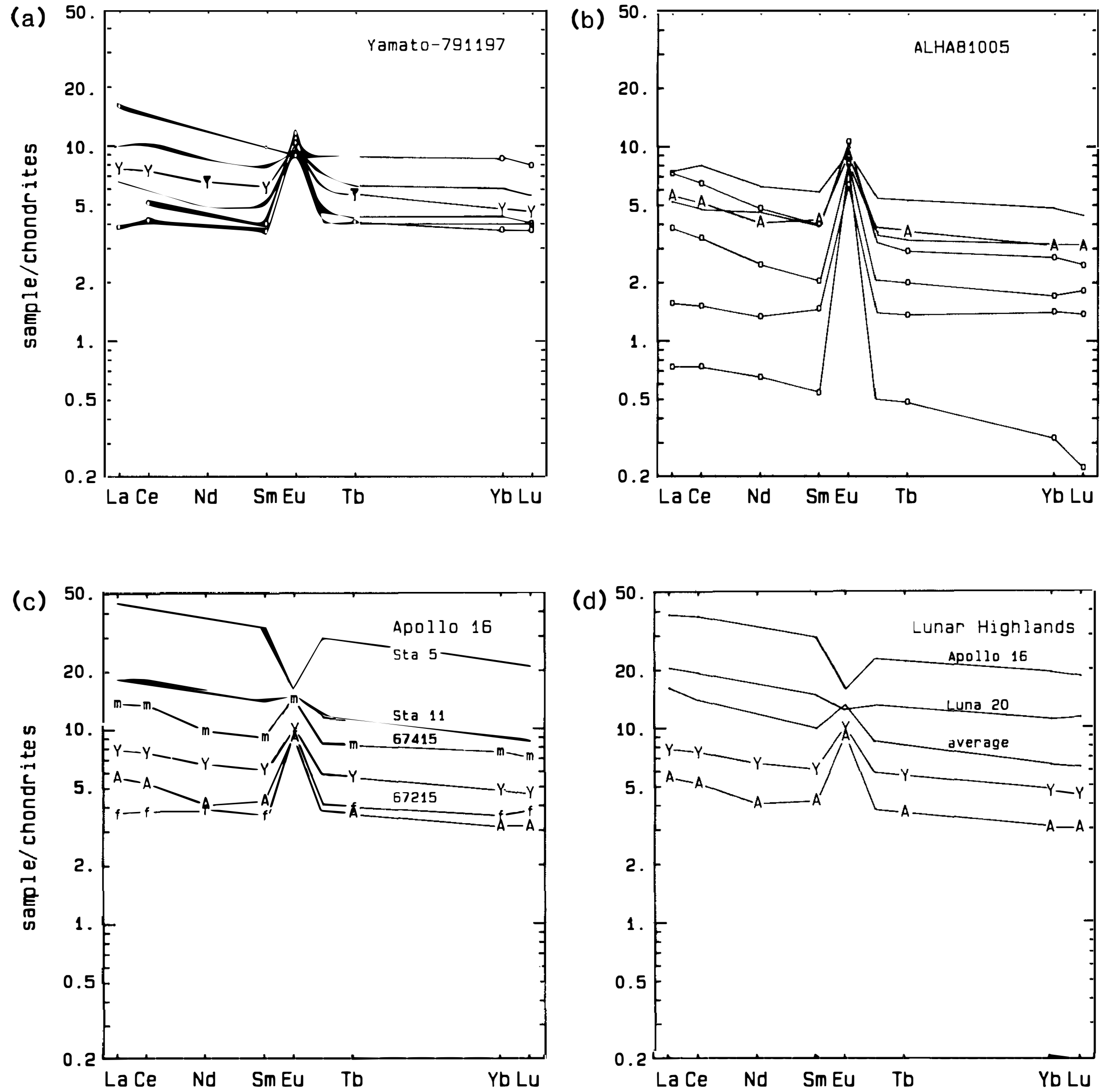

Fig. 1. REE patterns normalized to chondrites (*Nakamura, 1974*). (*a*) *Y-791197: Y–mass weighted mean of our analyses; lines-range of matrix or bulk literature analyses* (*Ostertag et al., 1985; Warren and Kallemeyn, 1985*); □*-individual clast analyses* (*Fukuoka et al., 1985; Nakamura et al., 1985; Warren and Kallemeyn, 1985*). (*b*) *ALHA81005: A–mean of our analyses* (*Korotev et al., 1983*); *lines-range of matrix analyses* (*Bogard, 1983*); □*-individual clast analyses* (*Bogard, 1983; Goodrich et al., 1984*). (*c*) *Apollo 16 soils and rocks: lines-station mean soil compositions with highest and lowest REE concentrations* (*Korotev, 1981*); *67215* (*f*) *and 67415* (*m*) *North Ray Crater rocks with compositions similar to lunar meteorites* (*Lindstrom and Lindstrom, 1986*). *Means of lunar meteorites shown for comparison* (*Y and A*). (*d*) *Regional lunar highlands composition. Average-estimate of average highlands composition* (*Taylor, 1982*) *based on remote sensing data; Apollo 16, Luna 20 mean soil compositions* (*Korotev et al., 1980*). *Means of lunar meteorites shown for comparison* (*Y and A*).

Comparison with other lunar samples (Figs. 1c, 1d) shows that the meteorites have REE concentrations lower than most Apollo and Luna polymict breccias and soils, but in the range of North Ray Crater (Apollo 16) rocks. The meteorites also have REE abundances in the range of lunar pristine rocks (Warren and Wasson, 1977; Warren *et al.*, 1983b). REE concentrations in the meteorites are higher than those of the ferroan anorthosites and lower than those of the Mg-suite and alkali anorthosites.

Sc, Cr, and Sr are compatible trace elements in lunar highland rocks. Concentrations of all three elements in both meteorites are within the range of Apollo 16 samples. Each element varies in concentration among samples from both meteorites, but ranges of concentration of Cr and Sr overlap for the two rocks; those of Sc do not. Y-791197 has Sc concentrations 1.6 times higher than those of ALHA81005. This is a large difference, considering the similarity for other compatible elements, but we note that Y-791197 also has a significantly lower bulk Mg′ value (61) than does ALHA81005 (74). Concentrations of siderophile elements (Co, Ni, Ir, Au) are variable in both meteorites, but their ranges overlap and are within those of Apollo polymict rocks. The concentrations and variations of all elements discussed here are consistent with a lunar highlands origin for Y-791197.

3.2. *Petrography and mineral composition*

Y-791197 is a fine-grained to glassy-matrix breccia containing numerous small mineral, glass, and lithic clasts. Most of the mineral clasts are plagioclase, but occasional clasts of iron-rich clinopyroxene and olivine are found. Lithic clasts, most of which are highly feldspathic (>70% plagioclase), include igneous and metamorphic rocks and impact melt rocks and glasses derived from the more primitive lithologies. As clasts, mineral fragments and impact-derived melt rocks are more abundant than igneous and metamorphic rocks, but the nature and frequency of the clasts of igneous and metamorphic rocks reveal the most about the source areas of the breccia. The major source lithologies are feldspathic rocks from the two major lineages, the ferroan suite (Mg′<70) and the magnesian suite (Mg′>70); minor source lithologies are differentiated lunar rocks and basalts from the lunar mare.

Because of the limited area of our grain mounts we did not attempt to do a thorough study of clast populations or mineral analyses of a large number of grains. Instead, we provide a general petrographic characterization of the breccia, determination of the range of clast types, and quantitative analyses of 19 clasts. The distribution of analyzed clasts (Table 2) is not representative of the breccia, because most igneous or metamorphic textured clasts were analyzed, but only typical examples of the more

Table 2. Clasts analyzed in Y-791197,89.

Polymineralic clasts	Monomineralic clasts
1 plagioclase vitrophyre	1 granular plagioclase
4 feldspathic melt rocks	1 pyroxene composite
1 noritic melt rock	1 exsolved pyroxene
1 noritic glass	1 olivine
2 ferroan anorthosites	1 granular spinel
1 ferroan anorthositic norite	
1 magnesian anorthositic norite	
2 mare basalts	
1 highly differentiated Fe-rich assemblage (exsolved pyx, plag, Fa, Fs-Hd, SiO_2, FeS)	

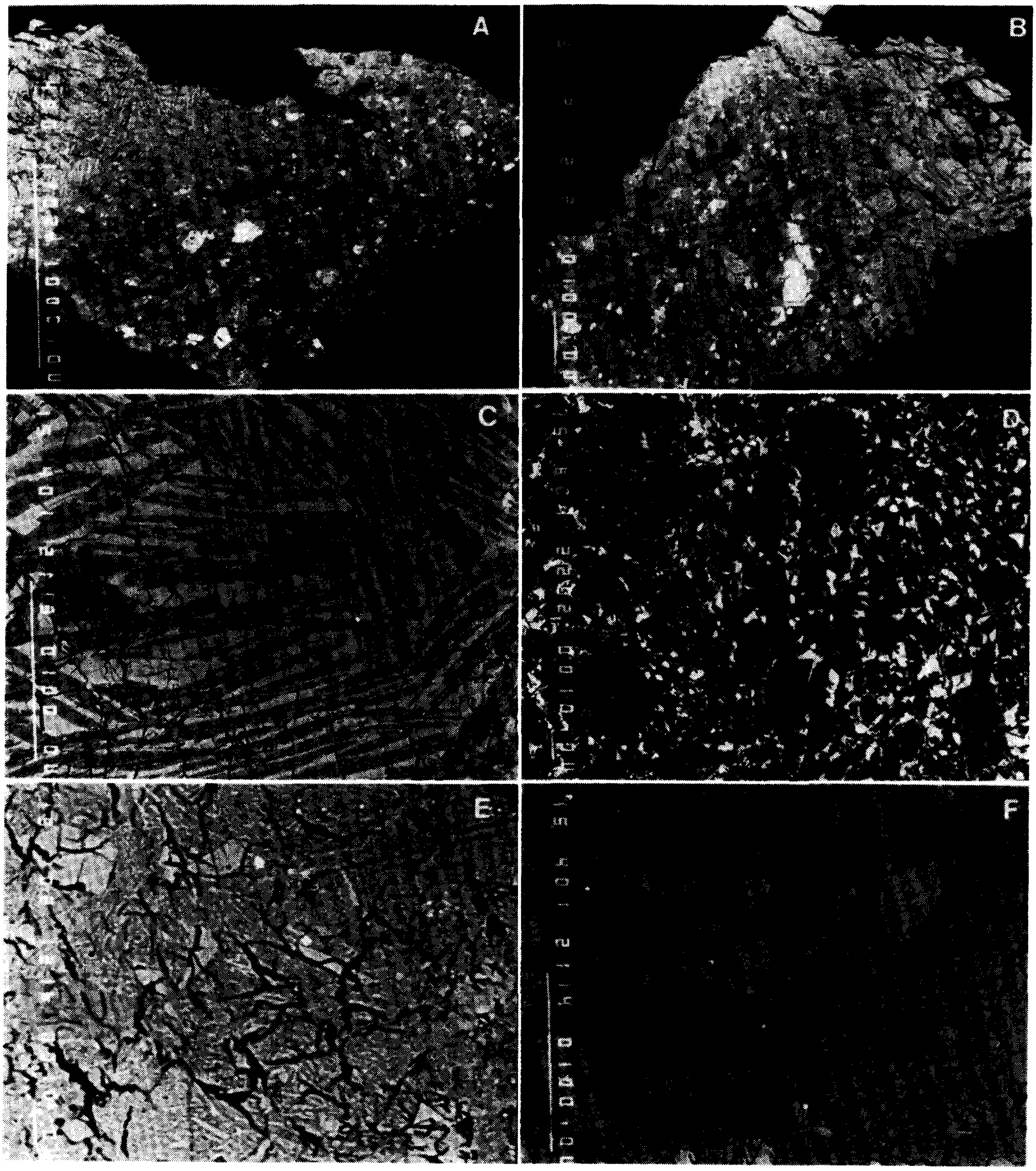

Fig. 2. Photomicrographs of Y-791197,89 taken in backscattered electron mode on the JEOL 733 Superprobe. Shadings represent average atomic number of the minerals, hence plagioclase is dark gray, Fe-rich mafic silicates are lighter, and Fe-rich opaque minerals are bright. Scale bars are shown in the lower left corner of each picture. (A) General texture of subsample 89,1, showing large plagioclase vitrophyre clast. (B) General texture of subsample 89,2 showing large clast of fine-grained feldspathic melt rock. (C) Plagioclase vitrophyre. (D) Feldspathic melt rock. (E) Magnesian melt rock. (F) Granulitic magnesian anorthositic norite.

abundant mineral, glass, and melt rock clasts were studied. Backscatterd electron images (Fig. 2) show the texture of Y-791197, but also provide qualitative data on modes and mineral compositions. Because intensity is dependent of the average atomic number of the mineral, plagioclase, mafic silicates, and oxides are easily distinguished

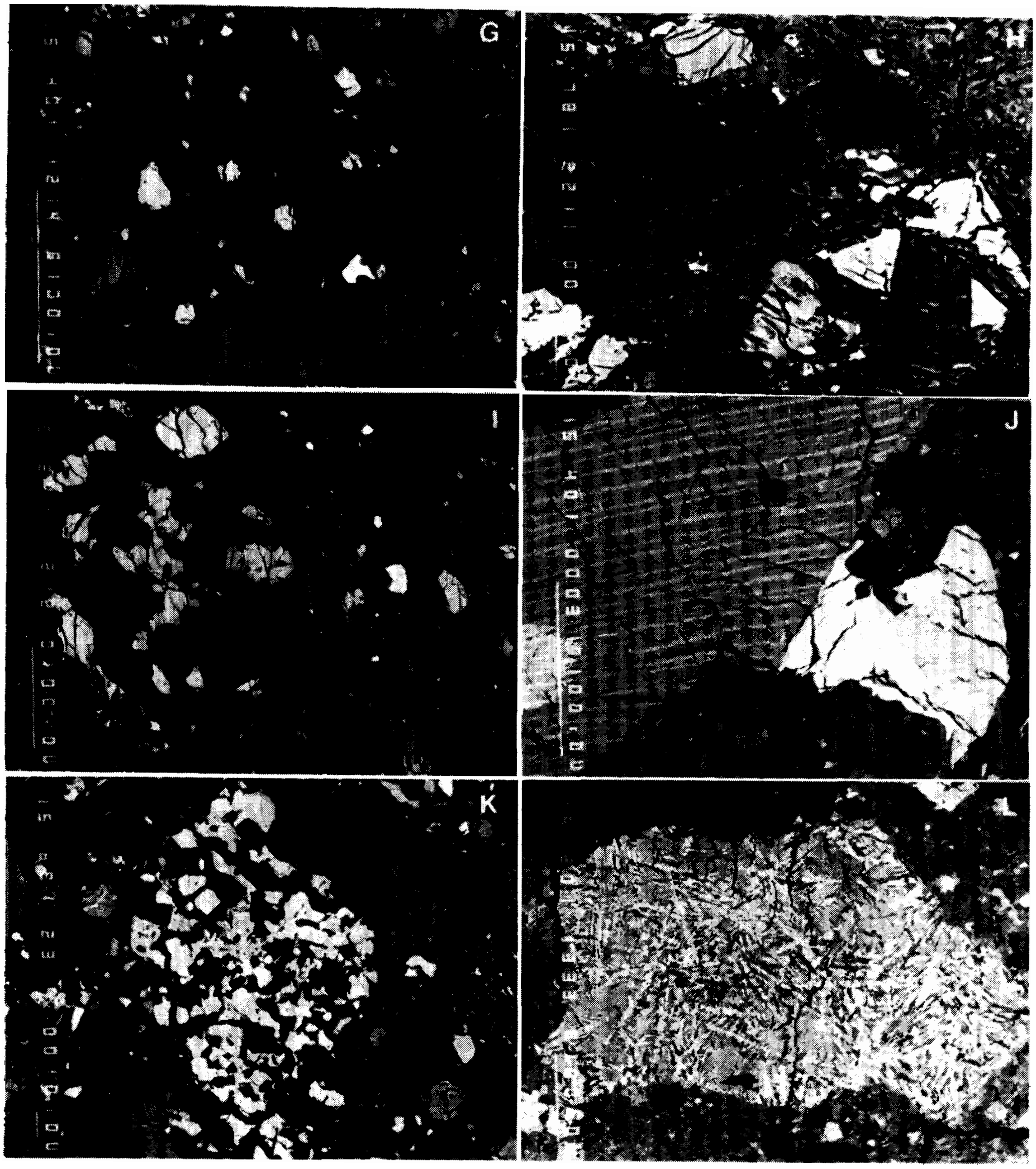

Fig. 2. (continued). (G,H) Ferroan anorthosites. (I) Ferroan anorthositic norite. (J) Highly differentiated assemblage consisting of exsolved clinopyroxene, fayalite, pyroxferroite-hedenbergite, troilite, silica and plagioclase. (K) VLT mare basalt, crystalline. (L) VLT mare basalt, quench-textured.

and Mg-rich silicates (dark) are distinct from Fe-rich silicates (bright). Figures 2a and 2b are low magnification images showing the general texture of the breccia. Figure 2a shows that the prominent green clast in subsample 89,1 is a large plagioclase vitrophyre, which is shown at higher magnification in Fig. 2c. Figure 2b shows that the gray clasts in 89,2 are fine-grained feldspathic ferroan melt rocks, shown enlarged in Fig. 2d. Figure 2e shows one of the rarer magnesian melt rocks. Bulk compositions of these melts and glasses (determined by defocussed beam analyses on electron microprobe) are given in Table 3. The most common melt rocks are ferroan anorthositic norites (26% Al_2O_3, Mg′ 55), but some have more noritic composition (16% Al_2O_3) with Mg′ varying from 60 to 75.

Table 3. Compositions of melt rocks and glasses.

	Feldspathic melt rocks				Noritic melt	Noritic glass	Plag. vitro	Quenched basalt	
								bulk	glass
	89,2	89,3	89,3	89,2	89,1	89,1	89,1	89,3	89,3
SiO_2	48	48	47	47	48	51	45	47	48
TiO_2	0.3	0.3	0.2	0.3	1.4	0.7	0.3	1.9	1
Al_2O_3	27	25	27	26	15.8	16	27	12.9	14.2
FeO	4.9	6.4	4.7	5.6	12.8	12.5	6.1	19.4	14.6
MgO	3.3	4.0	3.5	4.2	10.8	10.4	5.5	7.7	9.5
CaO	16.7	16.4	17.4	16.4	11.9	10.8	15.8	10.4	10.7
Na_2O	0.36	0.40	0.39	0.37	0.27	0.09	0.21	0.48	0.4
Mg′	54	53	57	57	60	60	62	41	54

Table 4. Mineral compositions in Y-791197.

	Plagioclase An range	Olivine	Pyroxene		Glass/Bulk	Other
			low-Ca	high-Ca		
		Mg′	Mg′	Mg′	Mg′	
Polymineralic lithic clasts						
Anorthosite 1	95.9–96.3	55		62		Ilmenite, chromite
Anorthosite 2	97.0–97.7		61	63		
Fe-anorth. norite	95.8–96.7			46		
Mg-anorth. norite	96.3–97.1	80	82	85		
Plag. vitrophyre	97.3–97.8				62	
Mare basalt (cryst.)	90.3–93.0			47		Ilmenite
Mare basalt (quench)	88.9				glass 55 bulk 41	Ilmenite
Differ. fragment	95.		39	44		Fayalite, pyroxferroite, hedenbergite, troilite, quartz, ilmenite
Monomineralic						
Granular plagioclase	95.6–95.8					
Olivine		51				
Pyroxene composite			45	57		
Exsolved pyroxene			39	44		
Granular spinel						Al_2O_3=64, FeO=10, MgO=21, Cr_2O_3=5 (wt%)

Igneous- and metamorphic-textured clasts are shown in Figs. 2f–2l, and mineral compositions for these and mineral clasts are summarized in Table 4. Shown in Fig. 2f is our only magnesian-suite clast, an anorthositic norite with granulitic texture. The next three clasts (Figs. 2g–2i) are ferroan: two anorthosites and an anorthositic norite with granular to cataclastic textures and variable assemblages of mafic minerals.

These four clasts are typical of the major igneous and metamorphic clast types found in Apollo 16 breccias. Figure 2j shows a very unusual clast which consists of a large exsolved clinopyroxene grain adjacent to an assemblage of fayalite, pyroxferroite-hedenbergite, silica, troilite, and plagioclase. Troilite appears both as a single large grain and as numerous small grains scattered through the pyroxene. A similar clast (HPF) was found by TAKEDA *et al.* (1985); it differs only in that it does not contain troilite or exsolved pyroxene and its plagioclase composition is An_{90} instead of An_{95}. The plagioclase in our clast is typical of that in the bulk rock, and other large, exsolved clinopyroxene grains are scattered in the matrix. Because exsolved pyroxene and plagioclase grains are found as clasts in the meteorite and because their compositions are incompatible with the extreme compositions of mafic minerals in the rest of the clast assemblage, we feel that the plagioclase and exsolved pyroxene grains adjacent to our clast are not part of the assemblage. We observed clasts with this unusual texture in lunar breccia 67016 (LINDSTROM and SALPAS, 1983), although the mineral compositions were less extreme. We interpreted the texture to result from metamorphism of a plutonic rock in the presence of a sulphur-rich fluid. The essentially Mg-free mafic minerals in this clast could be fragments of a very differentiated lunar rock, such as granite, or could represent the last stages of crystallization of a mare basalt, or result from metasomatism of an unspecified igneous rock.

The last two photos (Figs. 2k and 2l) show clasts of VLT (very low titanium) mare basalt, one subophitic-granular, and the other quench-textured. The granular basalt, which has a texture similar to some low-Ti mare basalts, consists dominantly of plagioclase and clinopyroxene, with minor ilmenite and little or no olivine. Its mineral compositions are within the range for Luna 24 VLT basalts. The quenched basalt has the texture of a pyroxene vitrophyre, with abundant clinopyroxene and less common plagioclase and ilmenite grains in the glassy matrix. Its bulk and mineral compositions are similar to those of VLT mare basalts.

Compositions of monomineralic clasts of plagioclase, olivine, and pyroxene (Table 4) are consistent with their derivation from the same parent rocks as the lithic clasts. The origin of the occasional large exsolved pyroxene clasts is uncertain. They are similar in composition to pyroxenes in both the ferroan anorthositic norite and the mare basalt, but they are larger and more coarsely exsolved than either of these potential sources. Analyses of Ti, Cr, and Mn in these pyroxenes do not resolve their origin, since they all plot near the mare-highland boundary (Figs. 2 and 5, TREIMAN and DRAKE, 1983). We feel that they may be too coarse-grained to be derived from a basaltic parent, and thus may represent a differentiated rock type not seen as lithic clasts. A single large clast of spinel was found and is probably related to the spinel-plagioclase (SA) clast described by TAKEDA *et al.* (1985). Such spinels are found in spinel troctolites in lunar breccias, but the absence of mafic silicates in either clast does not allow definition of their origin.

All of the impact-derived, lithic clasts and most of the mineral clasts appear to come from the same sources as the igneous and metamorphic clasts, which represent five distinct source lithologies: ferroan anorthosite, ferroan anorthositic norite, magnesian anorthositic norite, VLT mare basalt, and some type(s) of highly differentiated lunar rock. Y-791197 is dominated by the ferroan feldspathic lithologies. All of these source lithologies have been seen in ALHA81005 (KOROTEV *et al.*, 1983; RYDER and OSTERTAG, 1983; TREIMAN and DRAKE, 1983; WARREN *et al.*, 1983a) and in samples returned by the Apollo and Luna missions. Our petrographic description is consistent with those of other workers (YANAI and KOJIMA, 1984; OSTERTAG *et al.*, 1985; TAKEDA *et al.*, 1985), all of whom concur on the lunar origin.

4. Discussion

4.1. Lunar origin of Y-791197

The results of both geochemical and petrographic studies are consistent with an origin of Y-791197 on the lunar highlands. No chemical or petrographic feature of Y-791197 is inconsistent with a lunar origin. The meteorite's feldspathic bulk composition and clastic texture show that it is not derived from Earth's crust or from chondritic or achondritic meteorites. The factor of ten enrichment in Cr and depletion in Na relative to terrestrial anorthositic norites also distinguish the meteorite from its terrestrial counterparts. Polymict breccias are found among achondritic meteorites, but are mafic, not feldspathic like Y-791197. Other geochemical and petrologic data, radiogenic isotope variations, cosmic ray and solar wind induced features, magnetic characteristics, and spectral reflectance data all are indicative of a lunar origin for Y-791197 as outlined in this volume. There can be no doubt that Y-791197 is a lunar highlands breccia.

4.2. Comparison of Y-791197 with ALHA81005

Having concluded that Y-791197 is a lunar highlands breccia, we evaluate its relationship to ALHA81005 to determine whether the pair of meteorites represent the same impact or come from different regions of the lunar highlands. We have already noted that Y-791197 and ALHA81005 are similar in composition and clast assemblage; here we evaluate their differences in the context of the variability in characteristics of rocks from Apollo 16, the Apollo site most typical of the lunar highlands.

Compositions of the major minerals in igneous and metamorphic clasts from the two meteorites are compared in Fig. 3 to those from Apollo 16 rocks 67215 and 67415 and the fields of lunar pristine rocks (WARREN *et al.*, 1983b). Most data for the clasts plot within the fields of the two major highlands "pristine rock" suites: ferroan anorthosites, and the magnesian norites and troctolites. Highland source lithologies of the two meteorites are very similar to each other and to lunar highland plutonic rocks except that anorthositic norites, both ferroan and magnesian, are more common in the meteorites than among Apollo samples. The two meteorites differ significantly in their proportions of ferroan and magnesian clasts and in their bulk Mg′ value: Y-791197 is ferroan (Mg′ 61) and ALHA81005 is magnesian (Mg′ 74). This difference in Mg′ value extends to the impact-derived clasts in the meteorites. Most of the the melt rocks in Y-791197 are ferroan and most of those in ALHA81005 are magnesian.

Enrichments of Y-791197 relative to ALHA81005 in Sc by a factor of 1.6 and in REE by 1.3 were noted in Section 3.1. In Fig. 4, variations in Sc and Sm are plotted for the two meteorites and for non-pristine lunar samples which have similarly low concentrations of both elements. The two lunar meteorites form separate fields at low

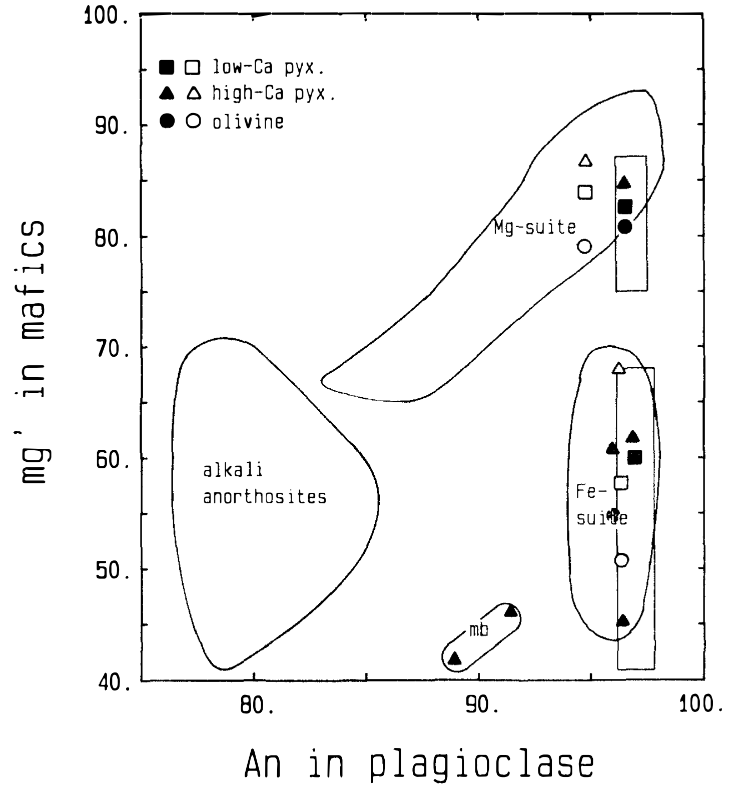

*Fig. 3. Compositions of major minerals in lunar meteorites and granulites compared to lunar pristine rocks (*Warren *et al., 1983). Filled symbols are clasts in Y-791197, open symbols are Apollo 16 granulites 67215 and 67415 (*Lindstrom *and* Lindstrom*, 1986). Boxes represent ranges for clasts in ALHA81005 (*Bogard*, 1983;* Goodrich *et al., 1984).*

Sm concentrations. Most Apollo polymict breccias and soils have much higher Sm concentrations (in fact, most samples from Apollos 14, 15, and 17 plot off the diagram). Most of the Sm and part of the Sc contained in Apollo 16 soils are provided by KREEP. Soils and fragmental breccias from North Ray Crater (Apollo 16) and granulitic breccias scattered throughout the highlands are the only groups of non-pristine rocks whose compositions are similar to those of the lunar meteorites. Lunar granulitic breccias (Warner *et al.*, 1977) have metamorphic textures, anorthositic norite compositions, and little or no KREEP component. We have shown that the granulitic breccias can be separated into ferroan and magnesian subgroups which are remarkably similar in composition to the lunar meteorites (Lindstrom and Lindstrom, 1986). These granulitic breccias are represented by rocks 67215 (ferroan) and 67415 (magnesian) in Table 1 and Figs. 2 and 3. In Fig. 4 these rocks and other lunar granulites are plotted as the letters f and m. The granulites occupy two distinct fields near those of the lunar meteorites. The field of magnesian meteorite ALHA81005 is between those of the ferroan and magnesian granulites, but closer to that of the magnesian samples. The field of ferroan meteorite Y-791197 overlaps with that of the ferroan granulites. This compositional similarity of polymict meteorites to monomict granulites suggests that anorthositic norites similar to the plutonic precursors of the granulites are the dominant source rocks of the lunar meteorites. The higher Sc concentration and lower Mg′ value

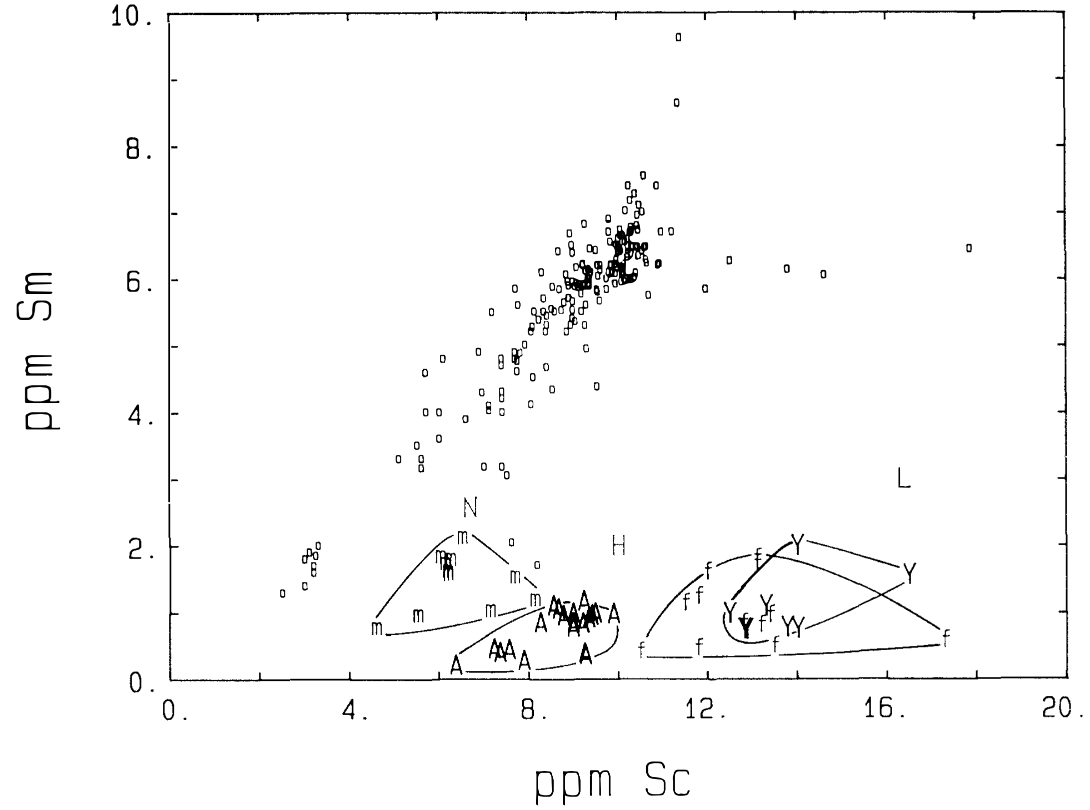

Fig. 4. Sm vs. Sc for lunar meteorites and other non-pristine lunar samples. Y–Yamato-791197 (our own and literature data this volume). A–ALHA81005 (BOGARD, 1983; GOODRICH et al., 1984). Granulites from Apollo sites, m–(magnesian), f–(ferroan) (LINDSTROM and LINDSTROM, 1986). H–average highlands composition (TAYLOR, 1982). Small points are individual Apollo 16 soils and cores. The average Apollo 16 soil composition (KOROTEV, 1981) plots in the middle of the densest cluster of points. Other average lunar soils are N, North Ray Crater and L, Luna 20 (KOROTEV et al., 1980).

of Y-791197 compared to ALHA81005 would then be due largely to a higher proportion of ferroan anorthositic norite. The exsolved clinopyroxene grains and VLT mare basalts are minor, Fe-rich components in both meteorites. These would enhance the differences in Mg′ and Sc concentration if they are more abundant in Y-791197 than ALHA81005.

In the previous paragraphs we have shown that, although the two lunar meteorites are compositionally and petrographically more similar to each other than they are to most Apollo samples, they still differ in some important ways. Are the similarities great enough that we can confidently conclude that the two meteorites were ejected from the Moon by the same impact? Or are the differences so great that a single impact could not have excavated and ejected material of such diverse composition? To attempt to answer these questions we consider breccias known to have been excavated by a single, small impact; the feldspathic fragmental breccias collected from the rim of North Ray Crater, whose diameter is only about one kilometer. We have shown that most of these breccias are composed of the same lithic and mineral components, but that the proportions of these components vary distinctly from one breccia to another (Lindstrom and Salpas, 1983). For example, typical breccias 67015 and 67016 both have ferroan anorthosites, granulitic magnesian anorthositic norites, and feldspathic, KREEP-poor melt rocks as major clast types. However, their less common clast types are more variable in distribution; ferroan anorthositic norites occur occasionally in 67016 but rarely in 67015, and KREEPy VHA basalt melt rocks occur commonly in 67015 but rarely in 67016. This clast variation leads to moderate differences in Mg′ for the two breccias (65 in 67016; 69 in 67015) and larger differences in KREEP dominated Sm concentrations (1.57 ppm in 67016; 4.04 in 67015). More extensive variation is seen in two atypical North Ray Crater samples. Breccia 67455 contains no magnesian or KREEP-rich components and has low Mg′ (55), and Sm (0.56) and high Sc (11.0). Breccia 67915 is dominated by magnesian granulite and has high Mg′ (78) and moderate Sc (5.8) and Sm (1.8). These compositional variations among breccias from the same crater exceed the variations between the two meteorites. We conclude that the differences between the two meteorites are not great enough to exclude the possibility that they were ejected by the same impact.

If the two meteorites were ejected by different impacts, then it seems probable that they would have come from locations separated by a distance large with respect to the areas excavated by those impacts. How different in composition and lithology are two separate areas likely to be? The orbital X-ray and gamma-ray data indicate that two locations selected at random on the lunar surface could differ significantly in average composition. Our experience from the six Apollo landing sites indicates that, for hand-specimen sized breccias, clast-type assemblages and bulk compositions are sufficiently different that a new sample known to be from one of those sites could be

Table 5. Clast assemblages of lunar regions.

Region	Igneous and metamorphic rocks				Impact-generated
	Ferroan	Magnesian	Differentiated	Mare basalts	Major melt rocks
A14	Rare anorthosite	REE-rich troctolite Rare anorthosite	Alkali anorth. Rare alkali gabbro	High-Al basalt	KREEPy norite (Fe-rich)
A15	Rare anorthosite Rare granulitic anorth. norite	Mod-REE norite and troctolite	KREEP basalt	Low-Ti mare basalt	KREEPy norite (Mg-rich)
A17	Rare anorthosite Gran. anorth. norite	Mod-REE norite and troctolite	Rare KREEP basalt	High-Ti mare basalt	KREEPy norite (Mg-rich)
A16	Anorthosite Rare noritic anorth. Gran. anorth. norite	Gabbronorite Spinel troctolite gran. anorth. norite	Rare sodic ferrogabbro Rare alkali gabbronorite	Various, but rare	KREEPy anorth. norite
Y-791197	Anorthosite Anorth. norite	Rare gran. anorth. norite	Exsolved cpx HPF*	VLT basalt	KREEP-free anorth. norite (Fe-rich)
ALHA81005	Anorthosite Rare anorth. norite	Gran. anorth. norite	Exsolved cpx	VLT basalt	KREEP-free anorth. norite (Mg-rich)

* Takeda *et al.* (1985).

identified as to the site by those characteristics alone. That is, interregional differences exceed intraregional differences. Table 5 lists clast assemblages for the Apollo highland sites and the lunar meteorites. Although members of the ferroan and magnesian suites are found at each site, the relative proportions of rock types and their modal mineralogy and REE concentrations vary from site to site. Differentiated igneous rock types occur at each site, but differ dramatically in abundance from one site to the next. Mare basalts are found in highland breccias near mare terrain, but the basalt types are different at each site. Finally, the impact-derived melts take on the character of their source region, with most Apollo samples enriched in KREEP. In this light the remarkable similarity in clast assemblages of the two lunar meteorites, including unusual differentiated and mare basalt components, is very strong evidence that they derive from the same region of the Moon and were probably ejected by the same impact. This conclusion is further supported by the general rarity of lunar meteorites. The main caveat to the conclusion is that our knowledge of compositional variability in the major, farside highlands is very modest.

4.3. *Implications for lunar crustal evolution*

The strong similarity in composition between the lunar meteorites and the granulitic breccias has important implications for lunar crust composition and evolution. These meteorites are polymict breccias from an unknown region poor in KREEP. They exhibit a wide variety of clast types that include plutonic and metamorphic anorthositic norites with both ferroan and magnesian compositions. These anorthositic norites are much more common in the meteorites than in the pristine rock collection; indeed granulitic magnesian anorthositic norite is the dominant clast type of ALHA81005. The granulites are very old breccias, probably >4.2 Ga (TAYLOR, 1982), which apparently pre-date the introduction of KREEP to the lunar surface. Many of them have been sufficiently melted and metamorphosed that their precursor lithologies are hard to identify. Based on the bulk composition and petrography of relict clasts and matrices in the least metamorphosed granulitic breccias, we concluded that some are monomict breccias with precursors of plutonic ferroan anorthositic norite (67215) or of magnesian anorthositic norite (67415) (LINDSTROM and LINDSTROM, 1986). Other granulitic breccias are polymict but are dominated by anorthositic norite lithologies. As shown in Table 1 and Fig. 4, and discussed above, the lunar meteorites and granulitic breccias are more similar to the average highlands composition than are any Apollo or Luna soils. This suggests that the lunar meteorites are derived from a region of typical lunar highlands. This region is nearly free of KREEP components but near a source of VLT mare basalt; it is more likely to be on the lunar farside than the KREEP-rich nearside. This conclusion was also reached by other workers (OSTERTAG *et al.*, 1985; WARREN and KALLEMEYN, 1985).

Studies of the so-called pristine rocks from the Apollo collections (WARREN and WASSON, 1977, 1980) have shown that anorthositic norites are uncommon, whereas ferroan anorthosites and magnesian norites and troctolites are common. From this it has generally been assumed (*e.g.*, TAYLOR, 1982) that the anorthositic norite bulk composition of the highlands surface resulted from mixing of approximately equal amounts of ferroan anorthosites and Mg-suite mafic rocks. Magma ocean models for the evolution of the lunar crust (*e.g.*, WARREN, 1985) are based in part on this conclusion. Our studies of Apollo soils (KOROTEV *et al.*, 1980; KOROTEV, 1981), lunar meteorites (this work and KOROTEV *et al.*, 1983), and granulitic breccias (LINDSTROM and LINDSTROM, 1986) conclude that some quantitatively important Fe- and Mg-bearing rock types that contribute to the soils and breccias are not found among the suite of pristine rocks, and therefore the distribution of rocks in the pristine suite is not representative of that of the lunar highlands crust as a whole. The lunar meteorites and granulitic breccias are non-pristine rocks with anorthositic norite bulk compositions. However, they do not attain their compositions primarily by mixing of ferroan anorthosites and Mg-suite mafic rocks. Plutonic anorthositic norites, both ferroan and magnesian, are important source rocks for both types of breccias. Anorthositic norites occur as the only lunar rock type in the monomict granulites, as the dominant rock type in polymict granulites, and as an important component in the lunar meteorites. The paucity of anorthositic norites in the pristine rock collection probably results from regional variations in clast assemblages (Table 5) and the unrepresentative nature of the Apollo regions. Models of lunar crustal evolution based on the proportions of pristine rock types should be revised to account for a much larger proportion of plutonic anorthositic norite, both ferroan and magnesian.

5. Conclusions

(1) Meteorite Y-791197 is an anorthositic breccia from the lunar highlands. All features of its bulk composition and the petrology of its clasts and matrix are consistent with a lunar origin.

(2) The two lunar meteorites studied to date are very similar to each other in bulk composition and clast assemblages. However, significant differences between Y-791197 and ALHA81005 do exist in Mg′ value, in Sc and REE concentrations, and in the proportions of various clast types. Because similar differences exist among lunar breccias known to have been ejected by the same, small impact and because clast assemblages of lunar samples vary regionally, we conclude that despite their differences, the meteorites were probably ejected from the Moon by the same impact.

(3) The compositions of the lunar meteorites are very similar to those of granulitic breccias found at several Apollo highlands sites and are more similar to the average highlands composition than are those of most Apollo or Luna breccias and soils. The lunar meteorites are derived from a region of typical highlands, distant from KREEP sources, but near a source of VLT mare basalt. That region is more likely to be on the lunar farside than on the KREEP-rich nearside.

(4) Plutonic anorthositic norites, both ferroan and magnesian, are important precursors of both the lunar meteorites and granulitic breccias. The paucity of anorthositic norites in the pristine rock collection probably results from the unrepresentative nature of the regions of Apollo sites, and does not mean that anorthositic norites are unimportant in lunar crustal evolution. Models of lunar crustal evolution should be revised to account for significant amounts of plutonic anorthositic norite.

(5) The lunar meteorites are interesting and important lunar samples which are changing some of our ideas about lunar petrology and geochemistry. The two ad-

ditional lunar meteorites in the Yamato collection (YANAI and KOJIMA, 1985) are important samples for future study, which will add to our knowledge of the lunar surface, affect models of cratering mechanics, and contribute generally to meteoritic research.

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