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GEOCHEMISTRY OF YAMATO-82192, -86032 AND -793274 LUNAR METEORITES

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Abstract: The major and trace element compositions of lunar meteorites Yamato (Y)-82192, Y-86032 and Y-793274 were determined by neutron activation analysis. Y-82192 and Y-86032 are anorthositic lunar meteorites rich in Al_2O_3 and CaO and poor in FeO, MgO and incompatible elements. Although these meteorites are similar in composition to each other and other anorthositic lunar meteorites, they are distinct in several key compositional characteristics. Y-793274 is a basaltic lunar meteorite rich in FeO, MgO, Sc, Cr, Co, and incompatible elements and poor in Al_2O_3 and CaO compared to anorthositic lunar meteorites. It is similar in many ways to lunar meteorite EET87521 which is also a basaltic breccia. It is distinct from EET87521 in its higher proportion of highland material, its meteoritic contamination and regolith glass, and in the composition of its dominant basalt component. Y-793274 contains 65–75% magnesian VLT basalt, while EET87521 consists of ferroan VLT basalt. The eleven lunar meteorites probably represent eight distinct falls. Four are anorthositic and four are basaltic. This 50–50 proportion of highlands-mare material contrasts strongly with the 83–17 proportion derived from photogeologic mapping. The dominance of VLT basalt among lunar meteorites contrasts with its scarcity among Apollo samples. The resolution of these discrepancies awaits further studies of basaltic lunar meteorites and further discoveries of new lunar meteorites.

1. Introduction

Lunar meteorites are important samples of the lunar crust brought to the Earth by impacts into unknown regions of the lunar surface. They are presumed to be random samples of the lunar surface and represent areas unsampled by the Apollo and Luna missions which covered no more than 5% of the moon's surface. In order to evaluate the significance of the eleven known lunar meteorites, it is essential to know how many distinct meteorites they represent and how many impacts sent them Earthward.

The past year has brought several important discoveries of lunar meteorites and has significantly changed the picture of the lunar crust that they present. In mid-1989 there were six known lunar meteorites and all were thought to be anorthositic regolith breccias. Two additional anorthositic breccias were discovered in 1989, including the largest lunar meteorite, MacAlpine Hills 88105 (MAC88105). More important was the discovery of the first basaltic lunar meteorite, Elephant Moraine 87521 (EET87521; DELANEY, 1989; WARREN and KALLEMEYN, 1989). Since then two additional basaltic lunar meteorites, Asuka-31 and Yamato (Y)-793169, have been identified by YANAI (1990a, oral presentation) and one of the previously unstudied "anorthositic" lunar meteorites, Y-793274, has been found to be basalt-rich (see below). The discovery of not just one but four basaltic lunar meteorites significantly alters the interpretation of lunar meteorites and presents more questions than answers. Some of the answers may come from detailed studies of existing lunar meteorites, but others must await further discoveries of new lunar meteorites.

In this paper we describe the geochemistry of two anorthositic lunar meteorites, Y-82192 and Y-86032, and one basaltic lunar meteorite, Y-793274. We compare these samples with other lunar meteorites and with lunar samples, and examine the implications of these data for the nature of the lunar crust.

2. Samples and Analytical Procedures

Sample Y-82192,141 was a 35 mg split of the bulk breccia allocated to L. HASKIN. It was a clast-rich polymict breccia. The sample was split for thermoluminescence (TL) and track studies done by SUTTON and CROZAZ. After completion of TL studies both unanalyzed (,141A, 11.4 mg) and analyzed fractions (,141B, 16.1 mg) were analyzed by INAA at Washington University.

Sample Y-86032,71 (1.19 g) was subdivided in the NASA-JSC Meteorite Processing Laboratory for distribution to US investigators. We were allocated two matrix chips (,75–176 mg and ,76–122 mg), a glass vein (,102–38 mg) and two clasts (,101–59 mg and ,103–4 mg). Clast ,101 was the large white clast visible in hand specimen (YANAI and KOJIMA, 1987b) which is a fine-grained light brown anorthositic breccia containing large plagioclase clasts. Clast ,103 is very small and mixed with matrix and was not analyzed.

Y-86032 matrix, glass, and clast ,101 were subdivided to yield a small sample each for major element analyses by electron microprobe analysis of fused glass beads and larger samples for INAA at NASA-JSC. Upon completion of INAA, matrix sample ,75 and clast ,101 were transferred to M. LIPSCHUTZ for RNAA with his results reported in WANG and LIPSCHUTZ (1990).

Sample Y-793274,62 (132 mg) was a split of the bulk breccia. The sample is a complex polymict breccia rich in brown minerals and containing numerous tiny clasts and one small white clast which we were unable to separate cleanly from matrix. The sample also had relatively abundant green and brown devitrified glass. We subdivided ,62 into two whole-rock chips, one of which (,62A–26.3 mg) was analyzed by RNAA without prior INAA. The other was further subdivided into four samples which were analyzed by INAA at NASA-JSC prior to shipment to Purdue for RNAA. Sample ,62B (62 mg) is a bulk chip from which a small aliquot (11 mg) was taken for major element analysis of a fused bead. Chip ,62C (12.9 mg) is a matrix chip rich in brown minerals and poor in glass. Samples ,62D (4 mg) and ,62E (3 mg) are chips of green and brown glass, respectively. Individual grains of these glasses were analyzed for major elements by electron microprobe.

INAA of Y-82192 was performed at Washington University, while analyses of Y-86032 and Y-793274 were done at NASA-JSC. Analytical procedures in the two laboratories are very similar, being designed largely by the same researchers and using the same standards and computer programs. In both cases samples were irradiated at the University of Missouri Research Reactor (MURR) for 14–24 hours at a flux of 5×10^{13} n/cm²/s. Analytical procedures are similar to those of KOROTEV (1987), with data reduction done using the TEABAGS programs of LINDSTROM and KOROTEV (1982). Procedures at JSC were modified to include three radioassays instead of two and used updated versions of the TEABAGS programs and new FEAT data analysis programs which are also currently in use at Washington University. The FEAT programs compile the data, apply fission corrections, compare results on standards to literature values, and assist in identifying and correcting analytical problems.

RNAA of Y-793274 was performed at Purdue. Again the MURR reactor was used as samples were reirradiated for 20–26 days at a flux of 8×10^{13} n/cm²/s. Samples were processed chemically and counted as described in WANG and LIPSCHUTZ (1990). Sample yields were generally 50–90% except for Ag and Sb which were $\geq$30%. Monitor yields were 60–90%.

3. Yamato-82192 and -86032

Meteorites Y-82192 (36.7 g) and Y-82193 (27.0 g) were collected in close proximity to each other in the Yamato Mountains in 1983, while sample Y-86032 (648 g) was found in the same area in 1986. Preliminary examination of Y-82192 (YANAI and KOJIMA, 1985), Y-82193 (YANAI *et al.*, 1986), and Y-86032 (YANAI and KOJIMA, 1987b) showed them all to be lunar meteorites and they were classified as anorthositic regolith breccias. Numerous subsequent petrographic and geochemical studies verified that they are anorthositic polymict breccias of lunar origin.

Y-82192, Y-82193 and Y-86032 are fragmental breccias containing abundant mineral and lithic clasts and rare glass spherules. Mineral fragments are dominated by plagioclase, followed by pyroxene and olivine. Lithic clasts include feldspathic rocks, impact melt rocks and granulites (BISCHOFF *et al.*, 1987; TAKEDA *et al.*, 1987, 1989). Rare mare basalt clasts have been identified by GOODRICH and KEIL (1987) and BISCHOFF *et al.* (1987). The presence of glass spherules indicate that these meteorites are regolith breccias, although their scarcity shows that they are very immature regolith breccias. TAKEDA *et al.* (1987, 1989, 1990a) and BISCHOFF *et al.* (1987) conclude that the textures and clast assemblages of these lunar meteorites are very similar to those of feldspathic fragmental breccias (LINDSTROM and SALPAS, 1983; STOFFLER *et al.*, 1985).

Major and trace element analyses of Y-82192 and Y-86032 are given in Table 1, together with mean compositions from previous analyses of these and other anorthositic lunar meteorites. Major element compositions of both meteorites are those of feldspathic rocks with 25–30% Al_2O_3 and moderate *mg'* values [molar Mg/(Mg+Fe)] of 62–69. The Fe/Mn ratios of 68–76 are typical of those of lunar rocks. Con-

Table 1. Major and trace element composition of Y-82192 and -86032.

Sample	Y-82192	Y-82192	Y-86032	Y-86032	Y-86032	Y-86032	Y-82192/3	Y-86032	A81005	Y-791197	M88105
Split	,141A	,141B	,75	,76	,102	,101					,41
Type/Ref	bulk	bulk	matrix	matrix	glass	clast	mean[1]	mean[2]	mean[3]	mean[3]	powder[4]
wt (mg)	11.4	16.1	128.6	100.7	27.2	37.4					206
SiO_2 (%)			44.7	44.4	43.6	43.9		44.1	45.8		45.2
TiO_2			0.18	0.18	0.19	0.17	0.32	0.20	0.27	0.34	0.24
Al_2O_3			28.9	29.9	28.4	28.1	25.9	29.3	25.7	26.1	28.3
FeO	5.05	4.12	4.32	4.06	4.44	3.96	5.68	4.22	5.51	6.39	4.28
MgO			5.10	5.05	4.91	6.28	5.17	5.24	8.20	6.11	4.17
CaO	14.4	15.0	16.2	16.7	16.3	15.9	14.7	16.2	15.0	15.4	16.9
Na_2O	0.411	0.441	0.443	0.439	0.448	0.348	0.40	0.43	0.30	0.33	0.335
K_2O	<0.09	<0.08	<0.06	<0.05	<0.10	<0.05	0.023	0.02	0.023	0.027	0.034
mg'			68	69	66	74	62	69	74	63	63
Sc (ppm)	10.9	8.23	8.79	8.13	9.27	8.14	12.5	8.27	9.1	13.3	8.92
Cr	894	701	715	670	737	757	997	666	890	900	623
Mn			440	430	470	450	631	458	580	660	512
Co	15.8	13.0	14.6	14.2	15.6	11.6	17.8	14.4	21.0	18.7	14.7
Ni	140	110	131	134	143	88	134	131	198	174	155
Sr	163	180	168	170	176	151	160	161	135	134	162
Ba	29	25	23	37	28	25	23	27	28	31	37
La	1.18	1.06	1.28	1.21	1.25	1.09	1.21	1.33	1.98	2.11	2.59
Ce	2.90	2.76	3.52	3.35	3.26	2.99	3.05	3.51	5.20	5.49	6.69
Sm	0.596	0.534	0.637	0.602	0.612	0.532	0.63	0.63	0.95	1.05	1.21
Eu	0.886	0.939	0.926	0.927	0.943	0.769	0.83	0.93	0.69	0.78	0.83
Tb	0.140	0.123	0.131	0.133	0.137	0.113	0.16	0.147	0.214	0.253	0.26
Yb	0.59	0.48	0.608	0.581	0.600	0.563	0.71	0.60	0.84	0.99	1.04
Lu	0.100	0.082	0.086	0.081	0.087	0.081	0.11	0.087	0.124	0.146	0.146
Zr	37	36					27	27	27	32	35
Hf	0.46	0.43	0.45	0.46	0.46	0.40	0.58	0.47	0.73	0.84	0.94
Ta	0.060	0.058	0.057	0.057	0.054	0.043	0.038	0.06	0.093	0.103	0.115
Th	0.133	0.100	0.244	0.196	0.190	0.153	0.19	0.22	0.29	0.33	0.43
U	<0.08	<0.07	0.046	0.046	0.058	<0.05	0.045	0.051	0.098	0.12	0.11
Ir (ppb)	3.2	3.8	4.0	3.8	3.8	3.0	4.3	5.3	6.8	6.6	6.5
Au	2.5	6.6	3.0	3.1	3.9	<1	1.5	2.4	2.2	5.1	2.2

References: [1] Mean of bulk/matrix analyses in Bischoff *et al.* (1987), Fukuoka *et al.* (1986), Warren and Kallemeyn (1987), and Koeberl (1988). [2] Koeberl *et al.* (1989). [3] Warren and Kallemeyn (1987). [4] Lindstrom *et al.* (1990).

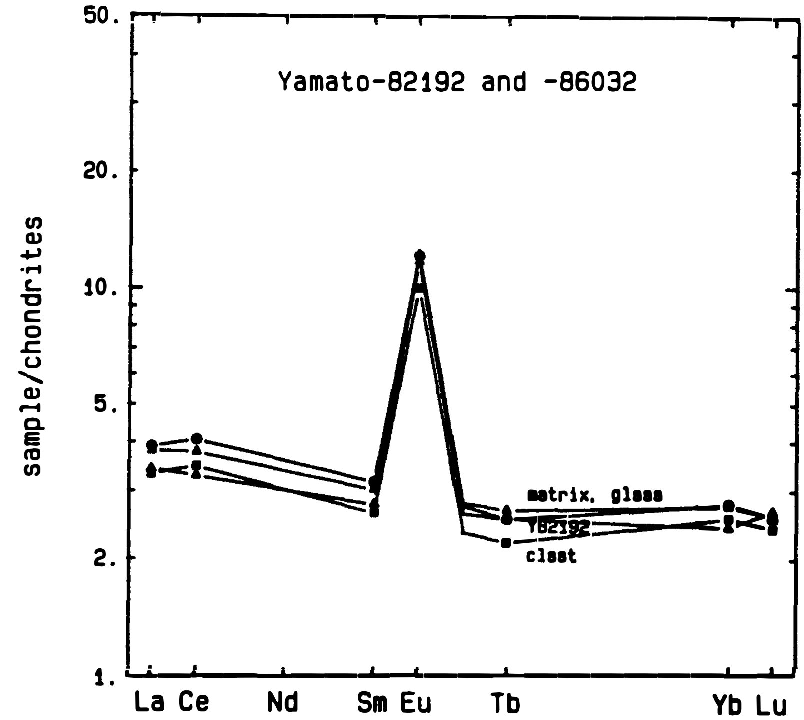
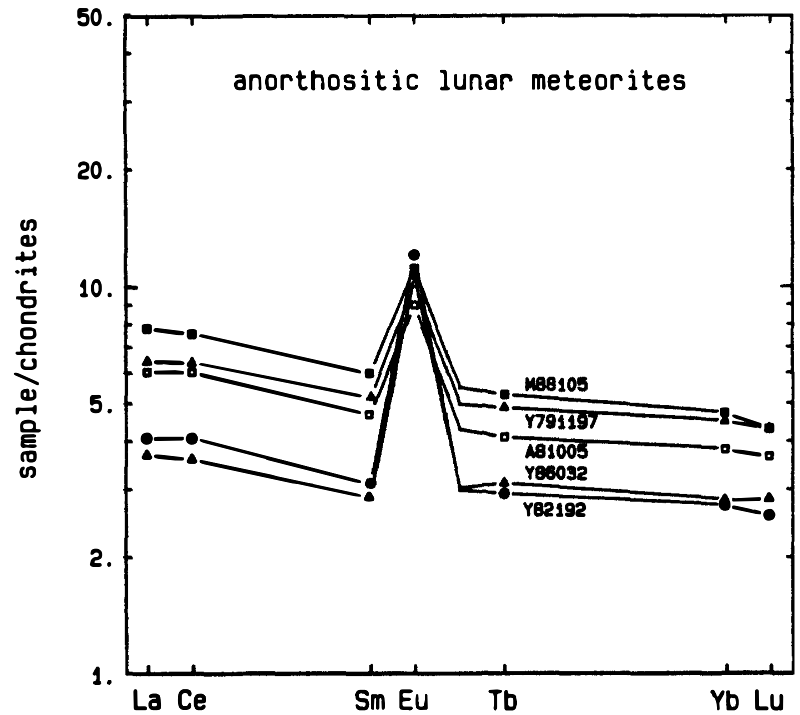
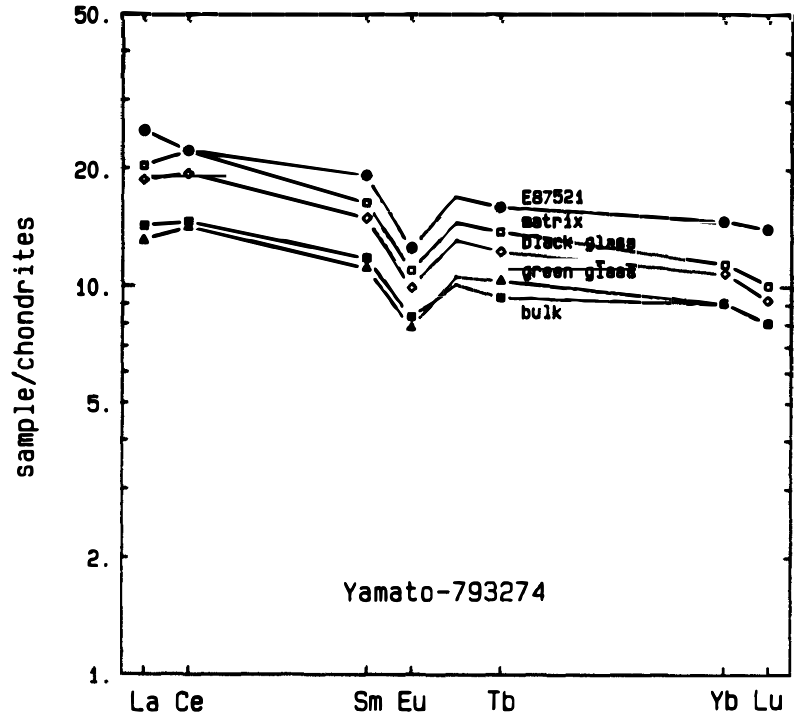


Fig. 1. REE analyses of lunar meteorites normalized to the average of ten ordinary chondrites (NAKAMURA, *1974*).

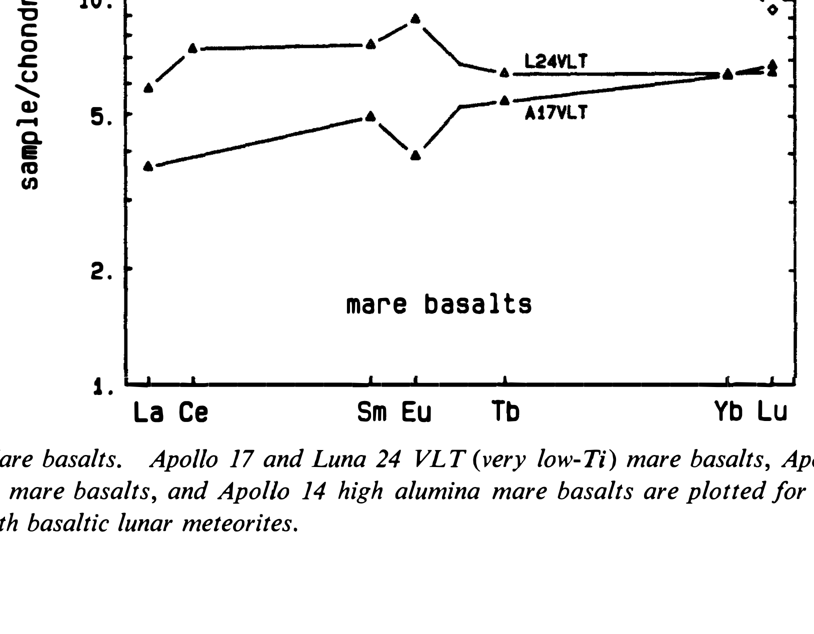
a. Y-82192 and -86032. Y-82192 is the mean of two new analyses. Matrix, glass, and clast are individual Y-86032 analyses.



b. Anorthositic lunar meteorites. Mean analyses of the five anorthositic lunar meteorites are plotted.



c. Y-793274. Four new matrix, bulk, and glass analyses of Y-793274 are plotted with EET87521 for comparison.



d. Mare basalts. Apollo 17 and Luna 24 VLT (very low-Ti) mare basalts, Apollo 15 low-Ti mare basalts, and Apollo 14 high alumina mare basalts are plotted for comparison with basaltic lunar meteorites.

centrations of trace transition metals Sc, Cr and Co are moderate, while concentrations of siderophile elements Ni, Ir and Au are indicative of meteorite contamination. Concentrations of REE and other incompatible elements (Ba, Zr, Hf, Ta, Th, U) are very low in both meteorites, and are the lowest of all lunar meteorites (Fig. 1a, b).

Our analyses of these meteorites are generally similar to the mean (Table 1) and within the range of previous analyses for most elements. Small samples such as the 11–16 mg splits of Y-82192 tend to deviate more from the mean than larger ones like the 100 mg splits of Y-86032. This is expected for small samples of heterogeneous polymict breccias like the lunar meteorites. The Y-86032 glass vein is essentially identical in bulk composition to the breccia matrix. Even the Y-86032 anorthositic breccia clast is very similar in composition to the matrix, differing mainly in its higher MgO and *mg'* value and its slightly lower siderophile and incompatible element concentrations.

Comparison of the mean compositions of the five anorthositic lunar meteorites shows that they are all very similar in their general compositional characteristics (high Al_2O_3, moderate MgO, FeO and siderophiles, and low incompatible element contents), but that they are distinct in their detailed composition. (Meteorites Y-82192/82193 and MAC88104/88105, respectively, are clearly paired specimens based on their geographic locations and all petrographic and geochemical characteristics, so that each pair is treated as a single meteorite although it is represented by two specimens.) ALHA81005, Y-791197, Y-82192 have 25–26% Al_2O_3, while Y-86032 and MAC88105 have 28–29%. ALHA81005 has a high *mg'* of 74, Y-86032 has a moderate one of 69, and Y-791197, Y-82192 and MAC88105 have low *mg'* of 63. Incompatible element concentrations are lowest in Y-82192 and Y-86032, intermediate in ALHA81005 and Y-791197, and highest in MAC88105. Although each meteorite exhibits some variability in composition, individual matrix or bulk analyses of one meteorite do not correspond to analyses of another meteorite in all characteristics, and the meteorites can be distinguished from one another.

As an example, the ranges and means of some key element concentrations in Y-82192 and Y-86032 are given in Table 2. The ranges of compositions of these meteorites overlap for some elements, but the mean compositions are distinctly different. There is considerable overlap in ranges and similar means for MgO, and

Table 2. Ranges and mean compositions of Y-82192 and Y-86032.

	Y-82192 (8 analyses)		Y-86032 (7 analyses)	
	range	mean	range	mean
Al_2O_3	25.3 –27.2	25.9	27.5 –29.4	29.3
CaO	14.3 –15.4	14.7	15.7 –16.7	16.2
FeO	4.12– 6.26	5.68	3.74– 5.04	4.22
MgO	4.5 – 5.76	5.19	4.81– 5.94	5.24
mg'	62–64	62	64–71	69
Sc (ppm)	8.2 –14.5	12.6	7.3 – 8.8	8.3
La	0.87– 1.54	1.22	1.0 – 1.56	1.33
Sm	0.43– 0.68	0.62	0.57– 0.66	0.63
Hf	0.27– 0.92	0.61	0.24– 0.54	0.47

incompatible elements La, Sm, and Hf. There is, however, only little overlap in ranges as well as distinct means for FeO, Sc, and *mg'* value, and no overlap at all for Al_2O_3 and CaO. The differences in Al_2O_3, CaO, Fe, Sc and *mg'* might be caused by heterogeneity in relatively small samples of polymict breccias. However, the ranges represent seven or eight analyses of each breccia, and the analyses of each of the anorthositic lunar meteorites show remarkable consistency. If heterogeneity is the cause of this difference in composition, it is heterogeneity on a large (meteorite) scale and not on the small scale of the samples analyzed.

Two specimens are said to be paired if they represent the same meteorite. Usually it is assumed that they entered the atmosphere as a single rock which broke up during atmospheric entry or impact. The evaluation of pairing among lunar meteorites involves several factors. Meteorites can be confidently paired if they are found at nearby locations, have similar petrography and bulk composition, and have similar cosmic ray exposure histories. This is demonstrably the case for the pairs Y-82192/Y-82193 and MAC88104/MAC88105, where the pairs were collected in the same areas and are indistinguishable in petrography, bulk composition, and exposure histories. Y-86032 is generally considered to be paired with Y-82192/3 because it has similar petrology and exposure history (EUGSTER *et al.*, 1989), but due to the differences in bulk composition we cannot argue confidently that it is indeed paired with Y-82192.

Another possible relationship between the two meteorites should be considered. Y-86032 may not be paired with Y-82192/3 in the sense that they are the same rock, but they may have been ejected by the same impact and followed a similar trajectory to Earth. Since neither meteorite preserves a history of exposure on the lunar surface, they may both have been buried in the megaregolith. Whether Y-82192/3 and Y-86032 are paired or not, their similar exposure histories show that they are very closely related. They were ejected by the same impact and represent the same region of the moon.

Among the nine sites visited by Apollo and Luna missions only Apollo 16 and Luna 20 were in regions of typical anorthositic highlands. Comparison of the compositions of lunar meteorites with Apollo 16 regolith breccias (MCKAY *et al.*, 1986) shows extensive overlap in the ranges of major element and compatible trace element concentrations (Al_2O_3 25–30%, *mg'* 66–74, Sc 5–10 ppm). However, incompatible element ranges do not overlap at all (La 5–20 ppm). The anorthositic lunar meteorites have incompatible element concentrations a factor of 2–20 lower than Apollo 16 regolith breccias. This is attributed to a much higher KREEP component in the Apollo 16 regolith breccias than in the nearly KREEP-free lunar meteorites.

Lunar granulites or granulitic breccias (LINDSTROM and LINDSTROM, 1986) have compositions very similar to those of the anorthositic lunar meteorites (Al_2O_3 25–29%, *mg'* 60–75, Sc 5–14 ppm, La 0.7–5 ppm). They are metamorphosed breccias which are found at all Apollo sites and as common clasts in lunar meteorites. As metamorphic breccias, however, they are not good petrographic analogs for the lunar meteorites.

Feldspathic fragmental breccias are typical of the ejecta from North Ray Crater, Apollo 16. They are thought to represent the lower part of the megaregolith and have had little exposure to cosmogenic nuclides. The compositions of feldspathic fragmental breccias (Al_2O_3 28–30%, *mg'* 56–78, Sc 5–11 ppm, La 0.9–8 ppm; LINDSTROM and SALPAS, 1983) overlap extensively with those of lunar meteorites. The variability in incompatible element concentrations is related to the amount of KREEP-rich impact melt clasts, but typical feldspathic breccias such as 67016 contain only 2–3 ppm La. These feldspathic fragmental breccias provide the best analogs for petrographic and compositional characteristics of the anorthositic lunar meteorites.

4. Yamato-793274

4.1. Major elements and lithophile trace elements (INAA)

Meteorite Y-793274 (8.66 g) was collected in the Yamato Mountains in 1980. Preliminary examination by YANAI and KOJIMA (1987a) showed it to be a lunar meteorite and classified it as an anorthositic regolith breccia. Recently, the first detailed petrographic and geochemical studies of the meteorite (KURAT *et al.*, 1990; LINDSTROM and MARTINEZ, 1990; TAKEDA *et al.*, 1990b; WARREN, 1990; YANAI and KOJIMA, 1990) showed that it is rich in basaltic material and similar in some respects to lunar meteorite EET87521, a basaltic breccia (DELANEY, 1989; WARREN and KALLEMEYN, 1989). YANAI (1990a, b; oral presentation) recently described two other basaltic lunar meteorites, Asuka-31 and Y-793169, both of which appear to be mare gabbroic rocks.

Y-793274 is a fragmental breccia containing abundant mineral and lithic clasts and rare glass spherules. Mineral clasts are dominated by pyroxene, followed by olivine, and then plagioclase. Lithic clasts include anothositic to gabbroic rocks, impact melt rocks and granulites (YANAI and KOJIMA, 1987a; KURAT *et al.*, 1990; TAKEDA *et al.*, 1990b). The predominance of ferroan pyroxene among mineral fragments suggests that the meteorite is largely of mare origin. The presence of highland lithic fragments shows it to be a polymict breccia. The existence of glass spherules demonstrates that it is a regolith breccia, although their scarcity suggests that it is an immature regolith breccia (KURAT *et al.*, 1990; TAKEDA *et al.*, 1990b).

Major and trace element analyses of Y-793274 are given in Table 3, together with other analyses of this meteorite and analyses of other basaltic lunar meteorites and very low Ti (VLT) mare basalts. Y-793274 exhibits considerable variability in composition. Compared to our bulk sample the two small glass samples are richer in FeO, Sc, Cr, Mn, and Co and poorer in Al_2O_3 and MgO and have a lower *mg'* value. The matrix sample has lower FeO, Sc, Cr and higher Co, Ni, Ir and Au. All have Fe/Mn ratios (63–70) typical of lunar samples. These variations suggest that the glasses are richer in ferrobasalt and the matrix is poorer in this basalt than the bulk sample. The matrix sample is also more enriched in siderophiles due to meteorite contamination. REE variations in the four samples (Fig. 1c) are more complex. REE concentrations are lowest in the green glass, only slightly higher in the bulk sample, distinctly higher in the black glass and highest in the matrix sample. This variation does not appear to correlate well with the basaltic component and may be related to a separate KREEP component.

Comparison with the other analyses of Y-793274 shows more variability. The

Table 3. Major and trace element composition of Y-793274.

Sample	Y-793274	Y-793274	Y-793274	Y-793274	Y-793274	Y-793274	Y-793274	E87521	Asuka-31	A17VLT	L24VLT
Split	,62B	,62C	,62D	,62E	,93/94	,83/96	,82	,6		78526	
Type/Ref	bulk	matrix	grn gl	blk gl	bulk[1]	matrix[2]	bulk[3]	bulk[4]	bulk[5]	bulk[6]	bulk[4]
wt (mg)	62.3	12.9	4.0	2.9	28.9	24.4	43	278		533	
SiO_2 (%)	48.3		49.0	49.1			47.1	48.4	45.4	46.7	46.2
TiO_2	0.57		0.62	0.61		0.63	0.63	1.12	1.66	0.92	0.85
Al_2O_3	13.7		12.1	11.9		16.7	17.4	12.6	11.5	10.0	13.1
FeO	15.1	14.0	16.6	16.7	15.2	14.1	12.5	19.0	21.2	18.6	18.6
MgO	9.0		8.3	7.8		9.5	9.0	6.34	6.41	12.2	6.71
CaO	12.0	12.5	12.2	12.3	12.2	12.4	12.2	11.6	12.0	10.0	13.0
Na_2O	0.33	0.39	0.31	0.34	0.46	0.41	0.39	0.41	0.50	0.12	0.30
K_2O	0.06				0.07	0.09	0.11	0.07	0.04	0.01	0.03
mg'	52		47	45		54	56	37	35	54	39
Sc (ppm)	37.8	31.5	42.6	38.1	31.9	31.9	28	44.0		51	48
Cr	2200	2170	2470	2260	2010	1920	1960	1470	1160	5070	1600
Mn	1850		1880	1930	1680	1370	1340	1890	1940	2020	2200
Co	41.1	44.3	43.2	45.8	41.4	45.5	43	46		45.4	43
Ni	70	160			100	110	128	29			25
Sr	90	130			100		140	104			105
Ba	58	84			97	91	85	88			45
La	4.68	6.73	4.31	6.20	7.00	6.06	6.7	8.3		1.2	1.92
Ce	12.6	20.4	12.2	16.9	17.9	17.8	15.0	20.9			6.4
Sm	2.38	3.31	2.24	3.03	3.56	2.60	2.79	3.86		1.0	1.54
Eu	0.64	0.84	0.60	0.76	0.96	0.94	0.97	0.98		0.30	0.68
Tb	0.48	0.71	0.53	0.63	0.76	0.55	0.61	0.80			0.33
Yb	1.98	2.50	1.98	2.37	2.73	2.66	2.36	3.19		1.4	1.41
Lu	0.27	0.34	0.27	0.31	0.38	0.38	0.34	0.48		0.23	0.22
Zr	100	90			81		87	140			40
Hf	2.00	2.21	1.51	2.00	2.96	2.35	2.36	2.88		0.5	1.05
Ta	0.20	0.22	0.19	0.19	0.34		0.32	0.37		0.06	0.16
Th	0.53	0.92	0.48	0.66	1.05	0.90	1.07	0.98			0.20
U	0.19	0.25		0.37	0.26	0.18	0.23	0.23			
Ir (ppb)	2.5	5			6.2		6.2	<1.2			
Au	3.5	5			3		2.4	<1.2			

References: [1] KOEBERL *et al.* (1991). [2] FUKUOKA (1990). [3] WARREN and KALLEMEYN (1991). [4] WARREN and KALLEMEYN (1989). [5] YANAI (1990b). [6] TAYLOR *et al.* (1977) and LAUL and SCHMITT (1975).

analyses of KOEBERL *et al.* (1991) and FUKUOKA (1990) are similar to our bulk and matrix analyses. Both exhibit low Sc (32 ppm) and high REE (La 6–7 ppm) similar to our matrix sample. The major element analysis of WARREN and KALLEMEYN (1991) is distinctly richer in Al_2O_3 and poorer in FeO than our analyses. Trace transition metal concentrations (Sc, Cr, Mn) also suggest that their sample contains a smaller proportion of mare basalt than our samples. Siderophiles Co, Ni, and Ir are high and indicative of meteorite contamination and incompatible element concentrations are as high as in our matrix sample.

Comparison with the compositions of anorthositic lunar meteorites (Table 1) and basaltic lunar meteorites (Table 3) shows that while Y-793274 is intermediate in composition for most elements, it is much more similar to basaltic than anorthositic lunar meteorites. The Al_2O_3 contents of 12–17% are slightly higher than 11–13% in basaltic lunar meteorites, but markedly lower than 25–30% in anorthositic lunar meteorites. Conversely, the FeO contents of 12–17% are somewhat lower than 19–21% in basaltic lunar meteorites, but distinctly higher than 4–6% in anorthositic lunar meteorites. REE and other incompatible element concentrations are relatively high and have a KREEP-like pattern similar to that of EET87521 and distinct from the REE-poor patterns of anorthositic lunar meteorites. The composition of Y-793274 is that of a basalt-rich polymict breccia.

REE patterns of the basaltic lunar meteorites are compared with those of lunar basalts in Figs. 1c–1d. The basaltic lunar meteorites have much higher REE concentrations than Apollo 17 and Luna 24 VLT basalts and have LREE-enriched patterns, rather than the LREE-depleted patterns typical of mare basalts. Apollo 14 high-alumina basalts have similar REE patterns at higher concentrations than the lunar meteorites. Models for the origin of these high-alumina basalts involve assimilation of KREEP before eruption on the lunar surface. Basaltic lunar meteorites Y-793274 and EET87521 are breccias, so it is possible that their KREEP component could have been added in the brecciation process. Analyses of individual basalt clasts in these breccias and of the two gabbroic lunar meteorites (Asuka-31 and Y-793169) are necessary to determine whether the KREEPy REE patterns in the VLT basaltic breccias are inherent in the basalts or were added during brecciation.

Detailed comparison of Y-793274 with basaltic lunar meteorites EET87521, Asuka-31 and Y-793169 and lunar VLT mare basalts can be used to evaluate the basaltic component of Y-793274. (A preliminary major element analysis of Y-793169 presented by YANAI (oral presentation, 1990), is very similar to that of Asuka-31 but is not tabulated here.) Although Y-793274 has only three-fourths the FeO of the other basaltic lunar meteorites, it has higher MgO and Cr concentrations. This suggests either that the basalt component of Y-793274 is more magnesian than those of EET-87521, Asuka-31 and Y-793169, or that its highland component is a mafic Mg-rich rock. The former seems the more likely case, as suggested by the comparison to Apollo 17 and Luna 24 VLT basalts (Table 3). Apollo 17 VLT basalts are distinctly more magnesian (MgO 10–13%, *mg'* 50–55) than Luna 24 VLT basalts (MgO 5–7%, *mg'* 30–40). The more magnesian Apollo 17 VLT are also a factor of two richer in Cr.

Figure 2 plots the bulk compositions of lunar meteorites and VLT basalts on a

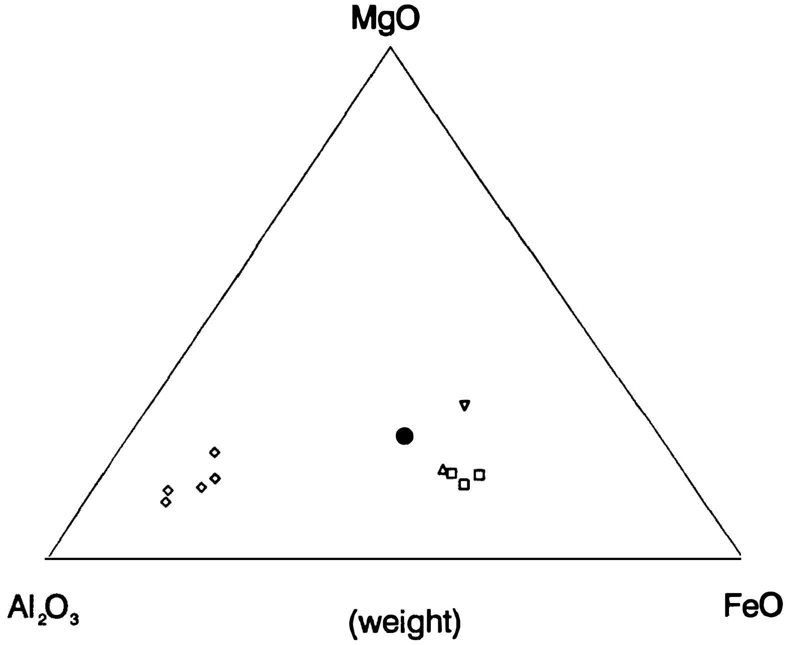


Fig. 2. Bulk compositions (weight percent) of lunar meteorites plotted as a triangular diagram of Al_2O_3-MgO-FeO. Anorthositic lunar meteorites (diamonds) plot near the Al_2O_3 corner. Basaltic lunar meteorites are FeO-rich. EET87521, Asuka-31, and Y-793169 (rectangles) cluster near Luna 24 VLT basalt (upright triangle). Y-793274 (black dot) and Apollo 17 VLT basalt (inverted triangle) are more MgO-rich. Breccia Y-793274 may be a mixture of magnesian VLT basalt similar to Apollo 17 and anorthositic highlands rocks.

triangular diagram of Al_2O_3-MgO-FeO in an attempt to interpret their components. Anorthositic lunar meteorites plot near the Al_2O_3 corner as would be expected for plagioclase-rich rocks. Basaltic lunar meteorites and VLT mare basalts plot in the FeO-rich area of the diagram. EET87521, Asuka-31, and Y-793169 cluster near the Luna 24 ferrobasalts, while Y-793274 and Apollo 17 VLT basalts are distinctly more MgO-rich. Polymict breccia Y-793274 appears to be a mixture of magnesian VLT basalt and anorthositic highlands rocks. Detailed mixing calculations are not very useful at present because of uncertainty in the component compositions. Based on compatible element concentrations of Al_2O_3, MgO, FeO, and Sc we estimate that Y-793274 contains approximately 65–75% magnesian VLT basalt similar to Apollo 17 VLT and 25–35% anorthositic component similar to anorthositic lunar meteorites. However, other element concentrations are not consistent with this simple model. Compatible elements Cr and Mn are probably inconsistent due to incorrect estimates of their contents in the basalt component. Siderophiles Co, Ni, Ir and Au require variable amounts of meteorite contamination, while high incompatible element concentrations require either a KREEP-rich basalt component or a discreet KREEP component. More detailed study of the basalt component of Y-793274 is needed to further define the mixing proportions, but magnesian VLT basalt makes up two-thirds to three-fourths of Y-793274, while the other three basaltic lunar meteorites consist almost entirely of ferroan VLT basalt.

TAYLOR *et al.* (1977) described the Apollo 17 and Luna 24 VLT basalt suites and suggested a fractionation model to relate the more primitive, magnesian Apollo 17 VLT samples to the more evolved, ferroan Luna 24 VLT rocks. WENTWORTH *et al.* (1979) continued the study with new samples and trace element analyses that showed that the Apollo 17 and Luna 24 VLT basalts were not petrogenetically related. Evaluation of whether the VLT basalts in the lunar meteorites are related by a simple fractionation process requires major and trace element analyses of the two gabbroic meteorites and of igneous clasts in the basaltic breccias.

Petrographic studies of lithic and mineral clasts in Y-793274 are also useful in evaluating the origin of the magnesian component of Y-793274. TAKEDA *et al.* (1990b) conclude that the magnesian pyroxenes in Y-793274 are of mare origin, while KURAT *et al.* (1990) suggest that they represent highland rocks. KURAT, however, compared Y-793274 mineral compositions with those of Luna 24 VLT basalts. The Y-793274 magnesian pyroxenes are very similar to pyroxenes in the more magnesian Apollo 17 VLT basalts. High-Ca pyroxenes such as the magnesian one tabulated by KURAT, are much more common in mare basalts than in highland rocks which generally contain low-Ca pyroxenes. Although further studies of lithic clasts should address this issue, the existing petrographic data are consistent with a magnesian VLT basalt as the major component of Y-793274.

The four basaltic lunar meteorites EET87521, Y-793274, Y-791369, and Asuka-31 were found in three distinct areas of Antarctica. They are distinct petrographically. EET87521 and Y-793274 are breccias, but Y-793274 contains a minor regolith component and EET87521 does not. Asuka-31 and Y-791369 are coarse-grained gabbroic rocks which differ somewhat in texture (YANAI, personal communication). All appear to consist largely of VLT mare basalt, but the basalt in Y-793274 is distinct from that in EET87521, Asuka-31 and probably Y-793169. It appears very unlikely that any of these four meteorites are paired, although they may have originated in a single impact from the same area of the moon. Petrographic and geochemical studies which evaluate the relationship between magnesian and ferroan VLT basalts and analyses of cosmogenic nuclides which provide exposure histories will be necessary to determine the number of impacts.

4.2. *Labile trace elements (RNAA)*

Results of RNAA for volatile and mobile trace elements in Y-793274 are given in Table 4 and C1-normalized concentrations are plotted in Fig. 3. Because of the small size of the two glass samples, the experimental precision is somewhat poorer than usual and results are given with a lesser number of significant figures in Table 4.

In its overall labile trace element pattern Y-793274 differs in several respects from other lunar meteorites studied to date. Typically, siderophiles (Au and Sb) and mobile trace elements (Se to Cd) each vary by ~4–5 times and show comparable C1-normalized concentrations in lunar meteorites and other lunar breccias. In contrast, siderophile and mobile element (Au, Sb, Bi and In) concentrations in Y-793274 are highly variable and C1-normalized concentrations are far from uniform: Au and perhaps Te are lower, and Sb, Bi and Ag seem higher than others. These trends do not seem to reflect Antarctic weathering but, rather, are of preterrestrial origin. Where Antarctic weathering effects appear in meteorites, they generally indicate trace

Table 4. Trace element concentrations in Y-793274 (RNAA).

Element (conc)	Bulk ,62A	Bulk ,62B	Matrix ,62C	Green glass ,62D	Black glass ,62E
Au (ppb)	0.31	10.7	0.98	0.31	0.78
Sb (ppb)	20	82	1.6	3.2	7.2
Se (ppb)	502	304	419	260	450
Te (ppb)	24±1	7.1±0.6	22±2	11±6	13±7
Bi (ppb)	6.69	3.12	4.1±0.5	9±2	18±2
Ag (ppb)	13.4	8.8	7.9	22	22
In (ppb)	1.46±0.08	1.77	1.51±0.20	0.8±0.3	5.0±0.7
Tl (ppb)	4.52	4.54	8.86	11	5.3±0.6
Zn (ppm)	4.56	6.88	11.7	3.2	7.3
Cd (ppb)	10.9	26.9	33.9	19±1	16±1
Rb (ppb)	697	322	1280	210	320
Cs (ppb)	38.2	42.2	72.6	27	46
Ga (ppm)	7.07	4.90	4.91	4.9	5.2
U (ppb)	190	223	283	160	230

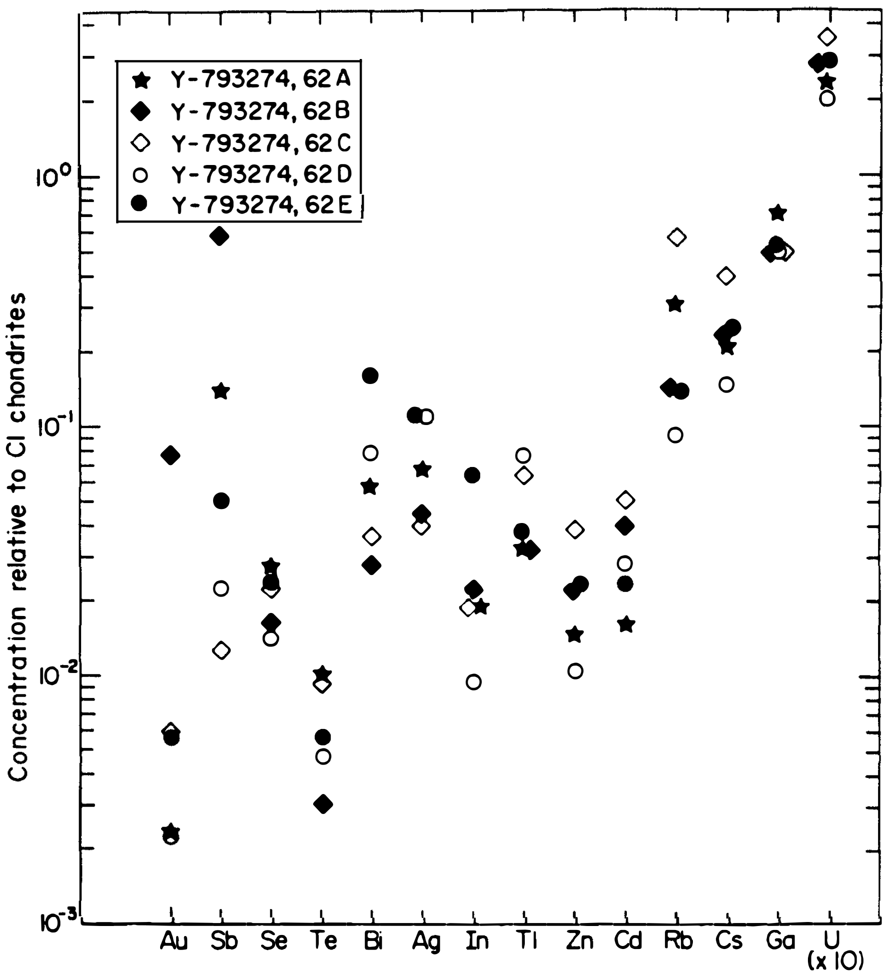


Fig. 3. Chondrite-normalized labile trace element patterns. Trace element concentrations (RNAA) in samples of Y-793274 are normalized to those of CI chondrites (ANDERS and GREVESSE, 1989).

element loss by leaching so that concentrations of elements affected by this process are lowered (DENNISON *et al.*, 1987). In Y-793274, concentrations of most siderophile and mobile elements are comparable to, or higher than, contents in other lunar samples. Furthermore, the two elements that should be most susceptible to Antarctic weathering, Rb and Cs (and other lithophiles Ga and U), show no evidence for leaching loss but rather exhibit trends very similar to those in other lunar samples. We suspect that the irregular trace element pattern of Y-793274 relative to those of other lunar (anorthositic breccia) meteorites studied to date reflects its strong igneous character, at least in part. Do some of the high trace element levels reflect a small degree of enrichment by volcanic emanations? Perhaps so in view of the presence of glass, but the evidence is suggestive and not conclusive.

Some support for the notion of a small degree of volcanic enrichment is obtained from the data of the two whole-rock samples ,62 A and B. Normally, concentrations of the 10 siderophile and mobile trace elements Au to Cd provide a measure of the micrometeorite component in lunar breccias such as lunar meteorites. For Y-793274 ,62A this proves to be a rather uncertain number, $2.6\pm2.1\%$ (C1-equivalent), comparable to those in other lunar meteorites (Table 5). For Y-793274,62B, on the other hand, the contribution calculated in this manner is unreasonably high and imprecise, 8.6 ± 18 (C1-equivalent). We interpret this as indicating that whole-rock sample Y-793274,62B is more enriched in condensed lunar volcanic emanations than is sample Y-793274,62A.

Surprisingly, the two glass samples Y-793274,62D and E show no systematic trends (Fig. 3), so that we can deduce only that they were as eager as or reluctant to condense lunar volcanic emanations as were whole-rock samples.

As noted, lithophile element trends are similar to those seen for other lunar meteorites. The KREEP component in the whole-rock samples Y-793274,62A and B can be estimated from their Rb and Cs concentrations. Relative to Y-82192/86032, the lunar meteorite(s) poorest in incompatible elements, Y-793274 contains a factor of 4 times more KREEP (Table 5), an amount comparable to that of Y-791197, the only other lunar meteorite containing condensed lunar emanations. With our limited data it is impossible to determine whether this is mere coincidence or has deeper significance.

Table 5. Components in lunar meteorites.

Lunar meteorite	Micrometeorite (% Cl-equivalent)	KREEP[1]
ALHA81005[2]	1.3 ± 0.5	1.9
Y-791197[3]	condensed volcanic emanation	4.0
Y-82192[4]	2.4 ± 0.8	(=1.0)
Y-86032[5]	2.5 ± 1.1	(=1.0)
MAC88105[6]	2.3 ± 1.4	3
Y-793274	2.6 ± 2.1	4

[1]Normalized ratios determined from Rb and Cs except for MAC88105 where only Rb was used.
[2]VERKOUTEREN *et al.* (1983); [3]KACZARAL *et al.* (1986); [4]DENNISON *et al.* (1987); [5]WANG and LIPSCHUTZ (1990); [6]LINDSTROM *et al.* (1991).

5. Discussion

There are currently eleven lunar meteorites in the Japanese and American Antarctic meteorite collections. These include seven anorthositic and four basaltic meteorites. Pairing of Y-82192 with Y-82193 and possibly Y-86032 and of MAC-88104 with MAC88105 reduce the number of separate anorthositic lunar meteorites to four. Although we have previously shown that Y-86032 is compositionally distinct from Y-82192/3 and may represent a distinct meteorite, the samples are obviously very closely related and ejected by the same impact. We therefore group them together hereafter. It is highly unlikely that any of the four basaltic lunar meteorites are paired. Table 6 summarizes the curation data for lunar meteorites. The paired, or possibly paired, samples are listed on a single line. The discovery of four basaltic lunar meteorites in the past year has drastically altered the proportions of highland/mare material represented by the lunar meteorites. Just a year ago there were five anorthositic lunar meteorites (eight specimens) and no basaltic ones, now there are four anorthositic and four basaltic lunar meteorites.

The anorthositic lunar meteorites are all regolith breccias. However, several of them are very immature regolith breccias having only minor regolith glass. These are more similar to feldspathic fragmental breccias than to mature regolith breccias. Several of the anorthositic lunar meteorites contain rare clasts of mare basalt, usually VLT mare basalt. The anorthositic lunar meteorites are all very similar to each other in bulk composition, but are distinct from each other in key compositional parameters such as Al_2O_3, *mg'* and REE concentrations. They are more similar in composition to each other than they are to most returned lunar samples, although some samples of feldspathic fragmental breccias and granulitic breccias provide very good matches to anorthositic lunar meteorite composition.

The basaltic lunar meteorites all have VLT mare basalt compositions, yet they are petrographically distinct. Y-793274 is an immature regolith breccia dominated by mare basalt, but containing a significant highlands component and rare regolith glass. EET87521 is a fragmental breccia composed of mare basalt with only a minor highlands component. Asuka-31 and Y-793169 are mare gabbros with coarse-grained igneous textures.

Table 6. Summary of lunar meteorites.

Discovery	Location/Number	Classification	Weight (g)
1982	ALHA 81005	Anorthositic breccia	31
1984	Y-791197	Anorthositic breccia	52
1985–7	Y-82192/3/86032	Anorthositic breccia	37/27/648
1987*	Y-793274	Basalt-rich breccia	9
1989	MAC 88104/5	Anorthositic breccia	61/662
1989**	EET 87521	Basaltic breccia	31
1990	Asuka-31	Mare gabbro	442
1990**	Y-793169	Mare gabbro	6

* Y-793274 was classified as a lunar anorthositic regolith breccia in 1987, but was found to be a basalt-rich breccia in 1990.

** EET87521 and Y-793169 were originally classified as eucrites.

Interpretations of the lunar meteorites are generally based on the assumption that they are random samples from several sites and that they may be representative of the lunar surface. In this regard it is essential to know the number of impacts or regions represented by the lunar meteorites. Pairing has reduced the number of meteorites from eleven to eight, or possibly nine, but it is possible that unpaired meteorites were ejected by the same impact. Cosmogenic nuclide studies are our best indicator of the number of impacts. EUGSTER (1989) summarized the exposure histories of the first five lunar meteorites and concluded that two or three impacts ejected those meteorites from the Moon. Subsequent studies showed MAC88104/5 to have a distinct exposure history and which led VOGT *et al.* (1991) to conclude that they were ejected by a separate impact. EUGSTER *et al.* (1991), however, concluded that the time of the impact that ejected MAC88104/5 barely overlapped the time of ejection of ALHA81005 and Y-791197. EUGSTER (1990) showed that Y-793274 has an exposure history very similar to that of ALHA81005. Y-793274, ALHA81005, and Y-791197, and perhaps even MAC88104/5, might all have been ejected by the same impact, yet they are very different meteorites and are definitely not paired. ALHA81005, Y-791197, and MAC88104/5 are anorthositic lunar meteorites, yet they include the most magnesian and most ferroan samples, while Y-793274 is a basaltic lunar meteorite. For these meteorites to have all been ejected from the same region, the region must have been extremely heterogeneous. It must be at a mare-highland interface and include a wide variety of highland components. The meteorites were collected in three widely separated regions of Antarctica and have different terrestrial ages, making the trajectories different. This complex scenario may be possible, but it is at least as likely that the meteorites were ejected by different impacts.

The eight lunar meteorites analyzed for cosmogenic nuclides were ejected by a minimum of two and a maximum of five impacts. Three of the basaltic lunar meteorites have not been analyzed for cosmogenic nuclides. These analyses are essential to evaluate whether any of the basaltic lunar meteorites are from the same impact, or whether they have sampled several separate mare regions.

Comparison of the lunar meteorites with Apollo and Luna samples can be useful in evaluating the nature and evolution of the lunar crust. Two major contradictions arise from these comparisons. The first is the distribution of anorthositic and basaltic lunar meteorites in contrast with the proportions determined from photogeologic mapping. The lunar meteorites are 50% anorthositic and 50% basaltic, while mapping yields 83% anorthositic and 17% basaltic areas. The second problem is that VLT is the dominant basalt type among lunar meteorites, yet a rare type among returned lunar samples.

Both of these problems might arise from unrepresentative sampling. Further studies of existing lunar meteorites and new discoveries of lunar meteorites should clarify the problem. If studies of the exposure histories of basaltic lunar meteorites show that some of them were ejected from the same region, despite the fact that petrographic and geochemical studies suggest that they are not paired, the conflict with mapping will be decreased or eliminated. The dominance of VLT basalt will also be less significant because each Apollo region is dominated by a single basalt type.

If new discoveries of lunar meteorites increase the proportion of anorthositic lunar meteorites, it will show that the current discrepancy in proportions arises from the unrepresentative statistics of small numbers of meteorites. If, however, the basaltic lunar meteorites were ejected by several impacts and the current proportion of anorthositic-basaltic lunar meteorites is upheld by further discoveries, one of our assumptions is in error. Either the lunar meteorites are not as random samples of the lunar surface as is currently assumed, or our knowledge of the lunar crust based on Apollo samples is incorrect due to unrepresentative sampling. This may indeed be the case since the Apollo and Luna missions collected samples from an area representing less than five percent of the lunar surface. More complete geologic investigations of the lunar surface are required to really understand the nature of the lunar crust. Lunar meteorites are wonderful, if sometimes perplexing, additions to the Apollo and Luna collections of lunar samples.

6. Conclusions

1) Y-82192 and Y-86032 are anorthositic lunar meteorites which are very similar in composition to each other and to the other anorthositic lunar meteorites. They are, however, distinct from each other and from the other anorthositic lunar meteorites in some key compositional characteristics. Although Y-82192 and Y-86032 are closely related and ejected by the same impact, we can not argue conclusively that they represent the same meteorite.

2) Y-793274 is a basaltic lunar meteorite. It is a basalt-rich breccia similar in many ways to EET87521. It is distinct from EET87521 in its higher proportion of highland material, its meteoritic contamination and regolith glasses, and in the composition of its dominant basalt component. Y-793274 contains 65–75% of magnesian VLT basalt like those at Apollo 17, while EET87521 consists of a ferroan VLT basalt like those at Luna 24.

3) There are currently eleven lunar meteorites which may represent eight distinct falls. These consist of four anorthositic and four basaltic lunar meteorites. This 50–50 distribution of highland-mare lunar meteorites contrasts strongly with the proportions derived from photogeologic mapping: 83% highland-17% mare.

All of the basaltic lunar meteorites are described as VLT basalts. VLT basalts are also found as clasts in several of the anorthositic lunar meteorites. This dominance of VLT basalt among lunar meteorites contrasts with their scarcity among Apollo samples. We do not expect that the samples collected by the Apollo and Luna missions which traversed less than 5% of the lunar surface are representative of the moon as a whole, but it is also likely that the lunar meteorites are not representative, and perhaps not as random as is generally assumed.

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