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LUNAR METEORITE YAMATO-86032: MINERALOGICAL, PETROLOGICAL, AND GEOCHEMICAL STUDIES

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Abstract: Yamato-86032 is a shock-lithified anorthositic fragmental breccia. It consists mainly of highly feldspathic meta-breccias and meta-meltrocks and possibly contains a small contribution from mare lithologies, but there is no indication of a KREEP component. In many respects Y-86032 is similar to the previously described lunar meteorites Y-82192/3, but there are some notable differences. We have analyzed about 40 major and trace elements in bulk matrix, impact melt, and clast samples from two chips of Y-86032. The abundances of most lithophile and incompatible elements are lower in Y-86032 than in Y-82192 (which contains very low abundances compared to normal lunar highland rocks). The REE abundances are comparable to those of Y-82192. The elements Sc, Cr, Mn, Fe and Co have significantly lower abundances than in Y-82192, and the siderophile element pattern is also different. Since cosmic ray exposure data indicate pairing of Y-86032 with Y-82192/3, the source region for these meteorites on the moon must have been fairly heterogeneous.

1. Introduction

The search for meteorites in Antarctica has so far yielded eleven lunar meteorites. Until recently, four samples have been known from the Japanese collection: Yamato (Y)-791197, Y-82192, Y-82193, and Y-793274. Three lunar meteorites have been identified in the U. S. Antarctic Meteorite collection: ALHA-81005, and very recently, MAC-88104 and MAC-88105. All samples with the exception of MAC-88105 are rather small (*ca.* 8–50 grams). During the 1986–1987 field season, the Japanese Antarctic Research Expedition (JARE) recovered a large meteorite (Y-86032) from the Yamato Mountains meteorite field, which was subsequently identified as a lunar meteorite (YANAI *et al.*, 1987; TAKEDA *et al.*, 1988, 1989a, b; KOEBERL *et al.*, 1989; EUGSTER *et al.*, 1989). All the above-mentioned samples are lunar highland rocks, but a short time ago EET-87521 has been identified as a mare sample (WARREN and KALLEMEYN, 1989).

Yamato-86032 is the second-largest lunar meteorite found so far (MAC-88105 weighs 662.5 g) and weighs 648.43 g. Like the other known lunar meteorites, it is an anorthositic breccia, indicating that the sample originated from the lunar highlands. Since only a small part of the lunar surface has been sampled by the Apollo and Luna missions, it is very important to have access to samples from other sites.

An important question concerns the number of impacts that are required to deliver the known lunar meteorites to earth. Since anorthositic regolith breccias are not common among Apollo rocks, it may be argued that it would be a coincidence if several different impacts supply the same rare type of lunar rock. On the other hand, chemical and isotopic arguments have been instrumental in showing that it is likely that more than just one impact on the moon has supplied the lunar meteorites (*e.g.*, EUGSTER, 1989), and that not all lunar meteorites are anorthositic regolith breccias (*e.g.*, TAKEDA *et al.*, 1989a, b).

2. Samples and Analytical Procedures

For petrological and geochemical studies, which are part of the consortium study of Y-86032 (H. TAKEDA, Consortium leader; TAKEDA *et al.*, 1988, 1989a, b; KOEBERL *et al.*, 1989; EUGSTER *et al.*, 1989), two chips (,84 and ,85) of the rock have been received from the National Institute of Polar Research. The samples have been subdivided into several bulk and clast samples for INAA and EPMA. Of subsamples, ,84A and ,85A, both bulk samples, and of ,85CL, a large white clast, polished thin sections were prepared for petrological studies. These samples were studied microscopically, and selected areas, clasts, and minerals were analyzed with an ARL-SEMQ electron microprobe following routine procedures.

The trace element analyses were made by INAA (instrumental neutron activation analysis), using methods that have been described previously (*e.g.*, KOEBERL, 1988a; KOEBERL *et al.*, 1989). The samples were sealed into polyethylene vials and subjected to two irradiations and up to five counting cycles, resulting in the determination of 38 elements. Some preliminary results have been reported by KOEBERL (1988b).

3. Sample Description

Initial petrological studies (YANAI *et al.*, 1987) suggested that the sample is an anorthositic regolith breccia, similar to Y-82192 and Y-82193. Visually the meteorite is similar to the other lunar meteorites, but its size (9.3 × 8.6 × 8.0 cm) is larger than expected from its weight. This indicates that the rock has abundant vesicles. Several large voids are visible from the outside.

A large part of the rock was reported to consist of anorthositic fragmental breccias with impact melt, which is partly glassy (TAKEDA *et al.*, 1989a, b). The impact melt is of yellowish-brown color and forms patches and veins within the breccia. On one side of our sample fragments of a greenish-yellowish fusion crust are present. Numerous large grey and white clasts—some are up to 1 cm in length—are embedded in the fine-grained matrix. Some similarities in the structure, mineralogy, and petrography between Y-86032 and Y-82192 suggest that these meteorites are paired (TAKEDA *et al.*, 1988, 1989a). Compared to other lunar meteorites (and also compared to known lunar regolith breccias), Y-86032 is very tough, and the matrix is very dense.

Bulk samples studied by us are compacted microbreccias consisting of mostly

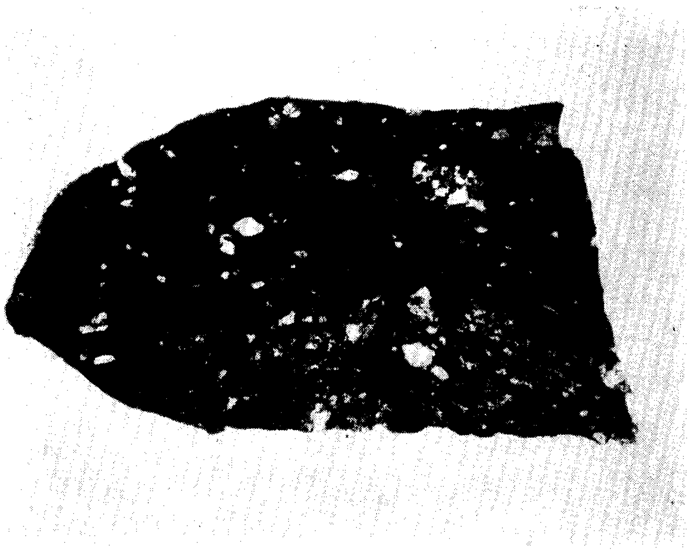

Fig. 1. Thin section of subsample Y-86032,84A in transmitted light. Maximum diameter is 4.2 mm.

Fig. 2. Thin section of subsample Y-86032,85A in transmitted light. Fusion crust covers the side opposite from the large light colored meta breccia clast. The bright, roughly triangular clast has a meta-igneous texture and is of gabbroic anorthosite composition. Maximum diameter is 5.8 mm.

light colored clasts and mineral fragments set in a dark matrix (Figs. 1 and 2). Most light colored clasts are recrystallized and shocked microbreccias very rich in plagioclase. Many of these clasts show diffuse outlines; some are rounded, and only a minority is subangular. Only one clast in Y-86032,85A has an igneous texture, consisting mainly of plagioclase laths with some interstitial pyroxene (gabbroic anorthosite—lightest clast in Fig. 2). Very fine-grained granulitic (better: hornfelsic) breccia fragments are fairly abundant, but always small (<300 μm). No basaltic clasts and no glass objects are present. However, some glass is occasionally present in microbreccia fragments and in the matrix. The whole rock apparently was shock-

Fig. 3. Thin section of subsample Y-86032,85CL in transmitted light. The troctolitic anorthosite breccia clast has granulitic texture with rounded olivine-plagioclase grain boundaries. Maximum diameter is 2.1 mm.

lithified and recrystallized.

Subsample Y-86032,85CL (Fig. 3) is a granulitic breccia clast with troctolitic anorthosite mineralogy. It is a metamorphic rock with rounded grain boundaries between the (Mg, Fe)-silicates and plagioclase. Plagioclase is strongly shocked and partly recrystallized. One side of the clast is covered by a dark matrix-like material which is intimately intergrown with the clast. It contains, however, mineral fragments of very much the same appearance as the minerals of the clast itself. The matrix is dense, apparently devitrified, glass with very abundant mineral fragments of highly variable sizes. Among these, two small sulfide grains (troilite) were encountered—the only ones found.

4. Results and Discussion

4.1. Bulk composition

The chemical composition of five samples of Y-86032 and comparison data for Y-791197 and Y-82192 are given in Table 1. In addition, Table 1 gives the weighted average of bulk samples of Y-86032 from 6 different laboratories (KOEBERL *et al.*, 1989). Two subsamples of Y-86032,84 ((I)=fine-grained matrix, probably recrystallized impact melt; (IM)=impact melt) and three subsamples of Y-86032,85 ((M)=matrix; (CL)=dark grey clast with some matrix; (WC)=small greyish-white clast) have been analyzed. The chemical data given here indicate some similarities between Y-821932 and Y-86032. The abundances of some lithophile and incompatible elements, including the rare earth elements (REE), in Y-86032 are similar to Y-82192. Figure 4 gives a plot of the chondrite-normalized REE abundances of four of the five samples analyzed in the course of this work. It was noted before (*e. g.*, WARREN and KALLEMEYN, 1986; OSTERTAG *et al.*, 1986), that ALHA-81005 is different in composition (including the REE pattern) compared to the other samples,

Table 1. Chemical composition of different bulk samples of the lunar meteorite Y-86032, and comparison data for other lunar meteorites.

wt. (mg)	Y-86032 ,84 [I] 75.20	Y-86032 ,85 [M] 34.48	Y-86032 ,84 [IM] 11.41	Y-86032 ,85 [CL] 6.87	Y-86032 ,85 [WC] 1.28	Y-86032 weighted average*	Y-82192 bulk [1]	Y-791197 bulk [1]	ALHA-81005 mean [2]
Major elements (wt%)									
Fe	3.20	3.50	3.43	3.05	2.89	3.27	4.85	4.99	4.27
Na	0.320	0.301	0.359	0.329	0.29	0.32	0.29	0.25	0.224
Trace elements (ppm)									
Cl	<30	<40	<40	—	—	<30	—	—	—
K	135	135	140	100	115	165	170	238	194
Sc	7.26	8.67	9.11	5.98	8.43	8.27	13.8	12.1	9.1
Cr	660	740	755	720	845	666	1156	889	890
Mn	390	520	479	445	580	458	746	674	580
Co	13.2	15.4	16.7	14.8	11.7	14.4	18.6	24.6	21.0
Ni	150	105	240	105	155	131	159	218	198
Zn	10	11.5	11	15	<10	9.1	—	—	8.7
Ga	4.8	3.53	5.4	4.0	3.27	3.66	10.4	3.3	2.7
As	0.27	0.28	0.30	0.38	0.26	0.27	0.028	0.3	—
Se	0.3	0.4	<0.6	<0.9	<3	0.40	0.3	0.56	0.6
Br	<0.2	0.1	<0.2	<1	<3	0.12	0.08	<0.08	0.19
Rb	<10	<6	<12	<15	<35	<1	3	8	1.5
Sr	118	156	150	104	<250	161	150	158	135
Zr	25	25	39	28	<50	27	30	35	26.8
Sb	<0.05	0.022	0.015	<0.09	<0.4	<0.015	<0.1	<0.1	—
Cs	0.05	0.03	0.035	<0.1	<0.9	0.05	0.08	0.08	0.024
Ba	30	28	21	48	<80	27	20	30	28.4
La	1.0	1.31	1.49	1.21	1.54	1.33	1.11	2.45	1.98
Ce	2.6	3.37	3.32	3.10	4.13	3.51	2.77	4.53	5.2
Nd	1.73	1.99	2.15	2.19	2.1	1.88	2.1	3.58	3.2
Sm	0.57	0.63	0.62	0.69	0.63	0.63	0.627	1.17	0.95
Eu	0.87	0.84	1.01	0.96	0.65	0.93	0.779	0.717	0.69
Gd	1.1	0.91	—	—	—	1.1	1.0	1.60	1.4
Tb	0.21	0.17	0.17	0.165	0.18	0.147	0.21	0.23	0.214
Dy	1.1	1.06	1.1	1.07	1.14	1.05	1.08	1.67	1.33
Yb	0.595	0.63	0.68	0.69	0.80	0.60	0.71	1.11	0.84
Lu	0.089	0.088	0.098	0.096	0.12	0.087	0.10	0.142	0.124
Hf	0.54	0.49	0.35	0.48	0.6	0.47	0.92	1.2	0.73
Ta	0.07	0.06	0.07	0.05	<0.5	0.06	<0.1	0.1	0.093
W	0.3	0.2	<0.5	0.24	—	0.36	—	—	—
Ir	0.0085	0.0013	0.007	0.0027	0.008	0.0053	0.010	0.0067	0.0068
Au	0.006	0.0013	0.003	0.0026	0.006	0.0024	0.0031	0.0066	0.0022
Hg	<0.07	—	—	—	—	<0.07	<0.05	<0.1	—
Th	0.22	0.20	0.19	0.27	0.20	0.22	0.23	0.34	0.29
U	0.07	0.07	0.06	<0.1	<0.8	0.051	0.066	0.10	0.098

* The weighted average column gives average data from six different laboratories (Koeberl *et al.*, 1989)
[1] Koeberl (1988a), [2] weighted mean of literature data, after Warren and Kallemeyn (1986, 1988, and references therein).

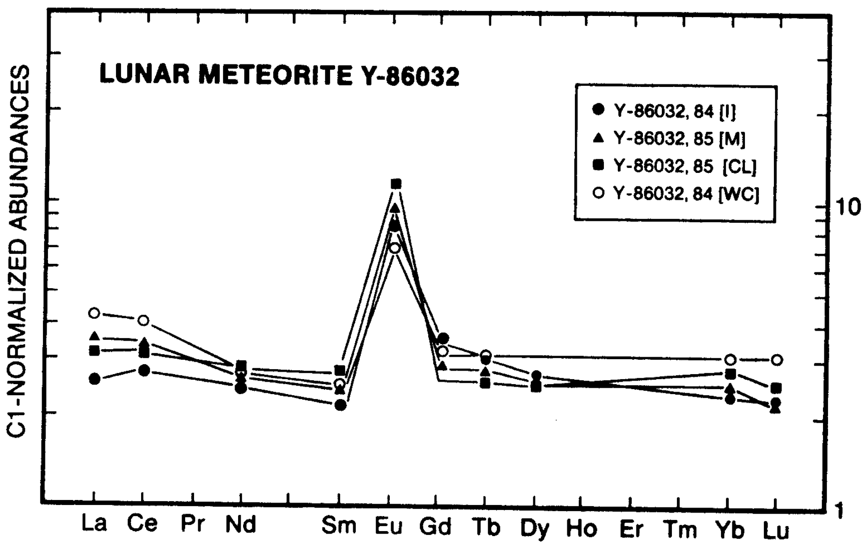

Fig. 4. Chondrite normalized REE abundance patterns of four subsamples of Y-86032 (CI data from TAYLOR, *1982).*

because it shows a small KREEP component.

At closer examination, the data reveals some interesting differences between Y-86032 and other lunar meteorites. The abundances of several elements, most notably Sc, Cr, Mn, Fe, and Co, are considerably lower in Y-86032 than in the other samples. The Sc-contents, for example, range between about 6 and 9 ppm in the individual samples, which is about 2/3 of the abundance observed in Y-791197 or Y-82192. The Cr, Mn, Fe, and Co abundances are lower in Y-86032 by a factor of about 1.3–1.5 compared to Y-82192. Because of the lower Mn and Fe contents of Y-86032, this sample shows a Fe/Mn ratio that is slightly different from other lunar meteorites and highland samples as given by OSTERTAG *et al.* (1986).

For many elements, the concentrations in Y-86032 are close to, but slightly lower than, the abundances in Y-82192 (Co, Ni, REE, Hf, Th). For some elements, the abundances in Y-791197 are lower than in Y-86032 (Sc, Cr, Mn, Ga). Some of the chalcophile elements do not show a consistent behavior. Arsenic has a much higher abundance in Y-86032 (similar to Y-791197) than in Y-82192, while Se in Y-86032 is similar to Y-82192. Some of the lower abundances are similar to the contents in ALHA-81005 (WARREN and KALLEMEYN, 1986), but otherwise ALHA-81005 does not fit the general elemental pattern (*e. g.*, for the REE).

The data on Y-86032 reported by other workers (WARREN and KALLEMEYN, 1988; KOEBERL *et al.*, 1989; EUGSTER *et al.*, 1989; see also average in Table 1) is consistent with the results obtained here. For most elements the agreement is excellent. WARREN and KALLEMEYN (1988) report slightly higher values for K, Mn and the LREE, while for Na, Sc, Fe, Cr, Co, and others the agreement is very good. The same good agreement is present between the current data and data reported by KOEBERL *et al.* (1989) and EUGSTER *et al.* (1989). The small differences between the abundances of some of the elements are most probably due to the inhomogeneity of the samples.

The siderophile elements also show an interesting trend. These elements, and

Se (and maybe a few others), may be used to investigate the imprint of a cosmic component. It is, however, not clear whether the cosmic component was delivered by the impact that led to the ejection of the rocks from the moon, or if it was deposited over a long time during the formation of the regolith (which seems to be a more plausible explanation).

The siderophile element pattern in Y-86032 is slightly different from the pattern observed in other lunar meteorites (which themselves do not show a uniform pattern). The abundances of Au and Ir vary between individual fragments (see Table 1), which is probably due to sample inhomogeneities. Analyses by other laboratories (see *e.g.* KOEBERL *et al.*, 1989) show similar variations. The siderophile element pattern of Y-86032 is different from the pattern for Y-82192 and Y-791197 as given by KOEBERL (1988a). The element Ni has lower abundances in Y-86032 than in other lunar meteorites (this is confirmed by other analyses; KOEBERL *et al.*, 1989), which is consistent with the lower abundances of Fe, Co, Cr, Mn, and other elements.

The major element bulk composition of Y-86032 was also estimated by analyzing the fusion crust on sample ,85A with the electron microprobe (Fig. 2, Table 2). The data are in excellent agreement with the INAA data (Table 1) and confirm the Fe-poor character of Y-86032. On the other hand, the chemical composition of the matrix of Y-86032 (Table 2) is richer in Fe and very similar to Y-82192/3 whole rock composition (*e.g.*, KOEBERL *et al.*, 1989). Y-86032 apparently is richer in a rock component consisting mainly of anorthitic plagioclase. These rocks, however, could have been mainly members of the magnesian highland suite because the Fe/Mg ratio of the bulk is clearly lower than that of the matrix and the other lunar meteorites with the exception of ALHA-81005 (PALME *et al.*, 1983). However, ALHA-81005 is petrographically very different from Y-86032 (*e.g.*, RYDER and OSTERTAG, 1983; KURAT and BRANDSTÄTTER, 1983; WARREN *et al.*, 1983a).

4.2. Phase compositions

Selected analyses of minerals from lithic fragments and of mineral fragments

Table 2. Electron microprobe analyses of the fusion crust and some matrix areas of Y-86032 (in weight-% ; N=Number of analyses).

Sample	Y-86032,85A		Y-86032,84A
Area	Fusion crust	Melt matrix	Matrix
N	21	6	5
SiO_2	46.2	42.5	44.4
TiO_2	0.13	0.21	0.21
Al_2O_3	30.1	29.3	27.9
Cr_2O_3	0.07	0.07	0.10
FeO	3.6	4.8	4.8
MnO	0.05	0.07	0.08
MgO	4.7	4.8	5.3
CaO	17.1	16.4	15.5
Na_2O	0.36	0.33	0.38
K_2O	<0.02	<0.02	<0.02
Total	102.31	98.48	98.67

Table 3. Electron microprobe analyses of co-existing phases in lithic fragments from Y-86032 (in weight-%). Px=pyroxene, An=anorthite, Ol=olivine; N=number of analyses.

Section	Y-86032,85A														Y-86032,85CL			
Rock	Metabreccia 85.3			Metabrec. 85.8		Melt rock 85.6			Melt rock 85.7			Metabrec. 85.10		Metabreccia				
Phase	Px	An	An	Px	An	An	Glass[1]	Glass[2]	Px	An	Glass[3]	Px	An	Ol	Px	Px	An
N	2	7	1	4	4	4	2	3	2	1	4	1	2	6	4	3	5
SiO_2	52.0	43.3	44.2	52.7	44.3	44.3	44.4	42.8	53.1	44.8	43.3	52.2	44.7	38.1	51.6	53.4	44.0
TiO_2	0.65	0.02	0.04	1.35	<0.02	<0.02	0.20	0.17	0.24	0.05	0.11	0.33	0.02	0.04	1.58	0.45	0.04
Al_2O_3	1.38	35.8	34.3	1.90	35.3	33.9	20.8	20.4	1.33	35.0	17.8	0.41	35.7	0.06	2.35	1.28	36.7
Cr_2O_3	0.53	<0.02	<0.02	0.54	<0.02	<0.02	0.05	0.11	0.62	0.02	0.05	0.27	<0.02	0.03	0.79	0.78	<0.02
FeO	15.6	0.20	0.39	6.5	0.32	0.23	9.6	12.1	18.7	0.64	13.8	21.9	0.29	24.9	6.9	14.8	0.20
MnO	0.30	0.02	0.02	0.19	<0.02	<0.02	0.12	0.17	0.33	0.02	0.16	0.36	0.02	0.30	0.21	0.27	<0.02
MgO	16.4	0.02	0.06	19.0	0.05	0.12	11.1	10.7	24.8	0.93	16.3	22.3	0.23	38.0	16.7	27.4	0.08
CaO	13.1	19.7	18.4	18.2	19.0	19.2	12.5	12.0	1.9	18.7	10.0	1.36	18.0	0.09	20.3	1.62	19.4
Na_2O	0.07	0.27	0.82	0.09	0.42	0.38	0.68	0.52	<0.02	0.44	0.54	<0.02	0.74	<0.02	0.06	<0.02	0.35
K_2O	<0.02	<0.02	0.05	<0.02	0.04	0.03	<0.02	<0.02	<0.02	0.02	<0.02	<0.02	0.03	<0.02	<0.02	<0.02	0.04
Total	100.03	99.33	98.28	100.47	99.43	98.16	99.45	98.97	101.02	100.62	102.06	99.13	99.73	101.52	100.49	100.00	100.81

[1] contains 0.35% NiO
[2] contains 0.20% NiO
[3] contains 0.4% NiO

Table 4. Electron microprobe analyses of mineral fragments from Y-86032 (in weight-%). Ol=olivine, An=anorthite, Ilm=ilmenite, Px=pyroxene, Pxf=pyroxferroite; N=number of analyses.

Section	Y-86032,84A		Y-86032,85A										
Phase	Ol	An	Ilm	Ol	Ol	Px	Px —	Exsol.	Px	Pxf	An	An	An
N	5	4	3	4	2	1	1	1	2	2	4	2	5
SiO_2	37.6	43.5	0.04	37.6	37.6	54.6	47.6	48.3	52.0	45.3	44.5	42.9	43.9
TiO_2	0.05	<0.02	54.3	0.05	0.06	0.76	0.56	0.99	1.12	1.01	0.04	0.03	0.06
Al_2O_3	0.02	36.9	0.14	0.04	0.03	1.37	0.34	0.92	2.39	1.35	35.5	36.0	36.0
Cr_2O_3	0.02	<0.02	0.10	0.05	0.06	0.49	0.05	0.09	0.83	0.02	<0.02	<0.02	<0.02
FeO	25.5	0.20	41.4	24.8	28.2	11.9	36.4	25.2	6.4	39.8	0.22	0.37	0.24
MnO	0.28	<0.02	0.47	0.29	0.29	0.25	0.52	0.31	0.19	0.54	<0.02	<0.02	<0.02
MgO	37.9	0.10	3.6	37.7	35.0	29.8	8.4	7.7	17.3	0.34	0.15	0.12	0.14
CaO	0.08	19.6	0.28	0.17	0.27	1.44	4.1	17.0	19.9	11.3	19.1	19.0	18.9
Na_2O	<0.02	0.29	<0.02	<0.02	<0.02	<0.02	0.03	0.06	0.06	<0.02	0.41	0.50	0.59
K_2O	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02	0.04	<0.02	0.03
Total	101.45	100.59	100.33	100.70	101.51	100.62	98.00	100.57	100.19	99.66	99.96	98.92	99.86

are given in Tables 3 and 4, respectively. Olivines and pyroxenes have compositions typical for lunar rocks (*e.g.*, FeO/MnO ratios, Fig. 5).

Olivines are abundant in some troctolitic anorthosite metabreccia lithic fragments, and as mineral fragments throughout Y-86032. Their chemical composition, however, appears to be restricted in range (Fa 23–30, Fig. 5) in our obviously non-representative sample. All olivines contain some Ti, Al, Cr, and Ca, although at a fairly low levels. The generally high abundance of olivines and their magnesian composition apparently reflects a fairly high abundance of troctolitic-anorthositic rocks of the magnesian highland suite in Y-86032. However, all of these rocks appear to be present as "granulitic" meta-breccias rather than pristine highland lithologies.

Pyroxene compositions show the usual range in molar FeO/(FeO+MgO) ratio from about 0.15 to 0.99 (Fig. 6). The majority is magnesian in composition (Fig. 7). Single grains and co-existing pyroxenes tend to exhibit equilibrated compositions, reflecting the high temperature metamorphic history of most of the lithologies of Y-86032. Most pyroxenes have compositions compatible with their provenance from the lunar highlands. The majority apparently was derived from the magnesian

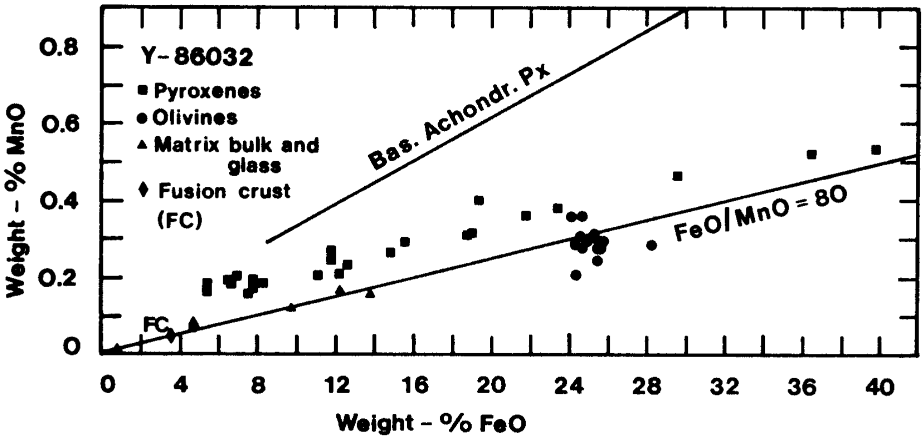

Fig. 5. Plot of weight-% MnO versus FeO of olivines, pyroxenes, glass-like matter, matrix, and fusion crust of Y-86032.

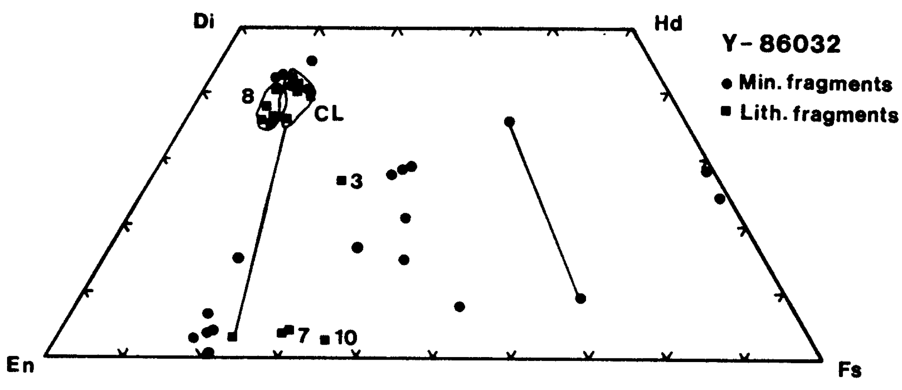

Fig. 6. Pyroxenes from Y-86032 plotted in the pyroxene quadrilateral. Dots are mineral fragments, squares are pyroxenes from lithic fragments. Tie lines connect co-existing pyroxenes.

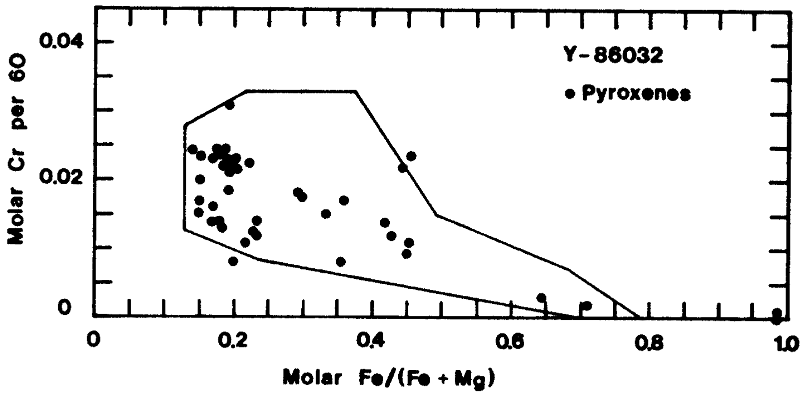

Fig. 7. Molar Cr content of Y-86032 pyroxenes versus molar Fe/(Fe+Mg) ratio. Outlined is the field for lunar terrae pyroxenes taken from BASALTIC VOLCANISM STUDY PROJECT *(1981).*

suite. Some contributions from ferroan anorthosite rocks are distinguishable. One grain, a low-Ca pyroxene with ferroan augite exsolution lamellae, could represent a small proportion of a hyper-ferroan anorthosite component as identified by TREIMAN and DRAKE (1983) in ALHA-81005. It could, however, also have originated from a gabbroic rock of mare provenance. Contributions from mare basalts appear to be minimal. One pyroxferroite grain was encountered (Table 4, Pxf). In addition, only one other grain with a Fe/(Fe+Mg) ratio of about 0.45 clearly projects off the major trend in Fig. 7 (at high Cr) and could be of mare origin. It is a subcalcic augite containing 1.6% Al_2O_3 and only 0.5% TiO_2.

Plagioclase compositions are overwhelmingly highly anorthitic, with a range between about An 98–85. Only a few grains or parts of grains showed An <95. They were found as isolated grains or parts of meta-breccia lithic fragments. Plagioclase commonly contains some TiO_2 (0–0.06 wt%), FeO (mostly 0.20–0.25 but sometimes ranging up to 0.65 wt%), and MgO (0.02–0.15%, occasionally up to about 1 wt%). Contents of K_2O are mostly below detection limit of the electron microprobe, but can reach up to 0.10 wt% in the most sodic plagioclases. Anyway, all plagioclase compositions encountered are compatible with a derivation from lunar highland rocks.

Combining the data on ferromagnesian minerals and plagioclase of lithic fragments (Fig. 8), it becomes apparent that Y-86032 metabreccias and meta-melt rocks were derived predominantly from ferroan anorthosite precursors with some contributions from the magnesian terrae rock suite. Our sample, however, is biased towards large fragments. If an appropriate sample of small granulitic clasts is included, the picture might change considerably.

Rare minerals encountered were two grains of troilite within the heavily shocked portion of meta-breccia ,85CL (it contains about 0.1 wt% Ni) and an isolated grain of ilmenite (MgO=3.6 wt%) (Table 4).

Some lithic fragments have been encountered which partially or exclusively contain a mafic glass-like melt instead of mafic minerals. This phase occurs interstitial to plagioclase and sometimes looks very much like interstitial pyroxene in SEM images. Its composition, however, is not that of a mineral, but rather that of glass (Table 3,

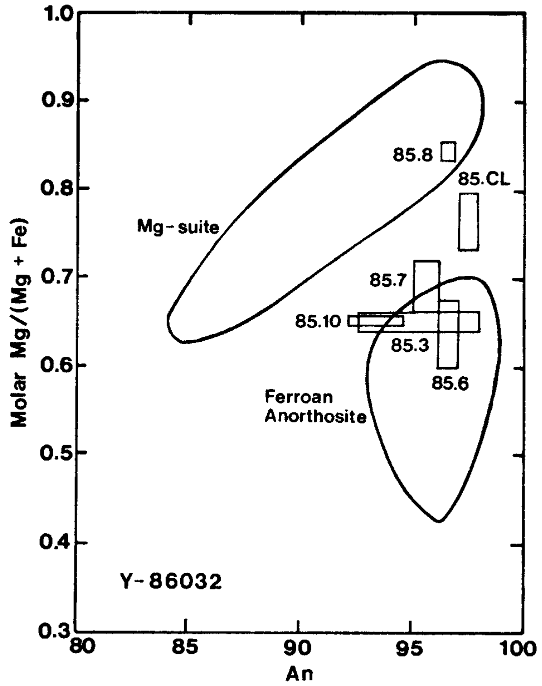

Fig. 8. Molar Mg/(Mg+Fe) ratio of ferromagnesian minerals versus An content of plagioclase of lithic fragments in Y-86032. The fields outlined correspond to the loci of projection of pristine lunar highland lithologies as defined by DOWTY *et al. (1974),* WARNER *et al. (1976), and* WARREN *et al. (1981, 1983b).*

melt rocks 6 and 7). It can be fairly homogeneous (no. 7) or somewhat inhomogeneous (no. 6). Its composition is that of an FeO- and MgO-rich ANT rock. It probably is of shock origin and represents local melt created by high residual shock temperatures which caused melting at plagioclase-ferromagnesian mineral grain boundaries but did not suffice to melt anorthite (which in all cases exhibits strong optical disturbances and some recrystallization).

All glasses analyzed contain NiO (0.2–0.4 wt%, Table 3). This could indicate an admixture of about 20% of a carbonaceous chondrite-like component, about 10 times more than the average highland regolith. The petrographic situation and the bulk chemical composition (Table 1), however, are not in straightforward support of that view. Either injection of a melt highly contaminated by the impactor, or mobilization and trapping of Ni could be responsible. The answer to that question will have to await further studies. No glass objects (spherules or clasts) were found in our sample. Unlike ALHA-81005, Y-86032 apparently is not of regolith origin, in accordance with noble gas data (*e. g.*, EUGSTER, 1989).

5. The Question of Pairing

It is important to know how many different source regions the lunar meteorites represent. ALHA-81005 and Y-791197 are typical regolith breccias (TAKEDA *et al.*, 1987) for which the time since the launch from the moon (*i. e.*, transit time plus terrestrial residence time) may be similar (0.17 Ma for ALHA-81005 and <0.12 Ma for Y-791197; NISHIIZUMI *et al.*, 1986). On the other hand, some cosmic ray exposure data (EUGSTER *et al.*, 1986) argue against a connection between ALHA-81005 and Y-791197. Other strong arguments are derived from the fact that they have quite different *mg*-ratios, which show a spread that is larger than the one observed in Apollo

16 regolith breccias from an 8.5 km traverse (WARREN *et al.*, 1987; WARREN and KALLEMEYN, 1987). In addition, it has been argued (WARREN and KALLEMEYN, 1987; KOEBERL, 1988a) that the trace element data are not consistent with the origin of ALHA-81005, Y-791197, and Y-82192/3 in a single impact.

Exposure history and terrestrial age determinations (EUGSTER, 1988a, 1989) and petrological studies (*e.g.*, TAKEDA *et al.*, 1987) have demonstrated that Y-82192 and Y-82193 are paired. Chemical data (*e.g.*, WARREN and KALLEMEYN, 1987; KOEBERL, 1988a) have indicated that these two meteorites are different from ALHA-81005 and Y-791197, *e.g.*, in having a lower *mg*-ratio, a higher Eu/Al-ratio, and different REE and siderophile element patterns. Yamato-82192/3 shows very low abundances of noble gases (*e.g.*, ^{36}Ar) trapped from the solar wind (indicating a rather short residence time on the lunar surface) and considerably lower cosmogenic noble gas abundances than ALHA-81005 and Y-791197 (BISCHOFF *et al.*, 1987; EUGSTER, 1988a, 1989).

Textural arguments, as well as mineralogical and petrological studies (TAKEDA *et al.*, 1988, 1989a, b; this work), suggest that Y-86032 is paired with Y-82192/3. Although the chemical composition of Y-86032 shows some similarities to Y-82192, a connection is by no means clear-cut. It has been argued above, on the basis of trace element data, that there are some differences between Y-86032 and any of the other lunar meteorites. In addition, the *mg*-ratio of Y-86032 is also different (WARREN and KALLEMEYN, 1988; Fig. 2 in KOEBERL *et al.*, 1989). However, the cosmic ray exposure age of Y-86032 (10.4 Ma; EUGSTER, 1988b, 1989) is identical to Y-82192/3 (more than 5, but less than 11 Ma; EUGSTER, 1988a, 1989). There is also some similarity between the terrestrial ages (72000+/−30000 years for Y-86032 *vs.* 83000+/−35000 years for Y-82192; EUGSTER, 1988c, 1989). EUGSTER (1989) concludes from his cosmic ray exposure data that two or three impacts have been responsible for delivering the known lunar meteorites (with the exception of Y-793274 and MAC-88104/5, for which no analyses are available at this time). New chemical analyses of MAC-88105 (KOEBERL *et al.*, 1990) show that this meteorite (and therefore MAC-88104, with which it is paired), seems to be different from all previously known lunar meteorites, therefore maybe increasing the number of impacts to four. However, confirmation of this has to await cosmic ray exposure data. On the other hand, the newly identified meteorite consisting of mare material (EETA-87521; WARREN and KALLEMEYN, 1989) certainly represents another impact, possibly the fifth. With an increasing number of impacts that delivered lunar material to the earth, the lack of such samples from the non-Antarctic meteorite collection begins to represent a problem.

6. Conclusion

Y-86032 is a shock-lithified anorthositic fragmental breccia consisting mainly of meta-breccias and debris thereof, meta-meltrocks, and possibly a small contribution from mare lithologies. No pristine rock nor mare basalt or a trace of KREEP lithology could be found in our sample. The precursor rocks comprise mainly coarse-grained granulitic and fine-grained hornfelsic metabreccias. Most of these rocks display a high degree of thermal metamorphism and high degrees of subsequent shock metamorphism.

Y-86032 appears to be rich in ferroan anorthosite and in a troctolitic anorthosite component of the highland suite. As a consequence, its chemical composition is poor in Fe, rich in Ca and Al, and has a low Fe/Mg ratio. The abundances of most lithophile and incompatible elements are lower in Y-86032 than in Y-82192. The REE and siderophile element patterns of Y-86032 are unlike ALHA-81005 or Y-791197, but are more similar to Y-82192. A chemical KREEP component is completely absent. The contents of the elements Sc, Cr, Mn, Fe, and Co are lower than in other lunar meteorites. On the other hand, textural, mineralogical, and petrological studies (TAKEDA *et al.*, 1988, 1889a, b; this work), and the close similarity in cosmic ray exposure ages (EUGSTER, 1988b, c, 1989), suggest pairing between Y-86032 and Y-82192/3. Two scenarios seem probable: either the similarity in cosmic ray ages is pure coincidence, or there was a large impact in a heterogeneous regolith target. The data seem to be more consistent with the second version, so that three different impacts seem to have been responsible for the first five lunar meteorites (ALHA-81005; Y-791197; Y-82192+Y-82193+Y-86032). Even if paired with Y-82192/3, Y-86032 is a valuable new sample, which, due to the differences in chemistry, must have originated from a somewhat different source than the other lunar meteorites. It should not be overlooked that rocks from the individual Apollo collections also came from relatively small areas on the moon.

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