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PETROGRAPHY, SHOCK HISTORY, CHEMICAL COMPOSITION AND NOBLE GAS CONTENT OF THE LUNAR METEORITES YAMATO-82192 AND -82193

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Abstract: The Antarctic meteorites Yamato-82192 and -82193 are lunar polymict shock-lithified fragmental breccias with a minor regolith component. They are probably paired. The breccias are composed of a great variety of lithic and mineral fragments embedded in a fine-grained, densely compacted clastic matrix. Recrystallized feldspathic rocks and breccias, and granulitic lithologies are by far the dominant rock types. Crystalline impact melt breccias are common, however the amount of devitrified glasses is negligible. Glasses, common in ALHA81005, are missing in Y-82192 and -82193. Both samples contain some large basaltic clasts.

All mineral and lithic clasts are shocked, and most plagioclases are recrystallized. We found no indication that the meteorite as a whole has been shocked to more than 20 GPa. These regolith breccias may have suffered peak shock pressures in the order of 10 GPa during the lithification event.

The chemical composition of Y-82192 is very similar to that of the other lunar meteorites. Major differences are the low absolute abundances of REE and their flat chondrite normalized patterns. Other incompatible elements such as Hf and K also have comparatively low concentrations similar to the REE. The siderophile elements Ni, Co, Ir, and Au have similar abundances to other lunar highland samples. There appears to be a uniform signature of siderophile elements in the old lunar highlands away from the large basins of the front side of the Moon.

The noble gas content of Y-82192 is entirely different from that of Y-791197 and ALHA81005. The light noble gasses He, Ne, and Ar are dominated by spallogenic and radiogenic components while the trapped gasses are similar to those in the Apollo 17 boulder and to those of "normal" meteorites. There is no indication that Y-82192 contains, or ever contained, any solar-wind implanted noble gases.

1. Introduction

Among the several thousand meteorites recovered from Antarctica there are four which are undoubtedly of lunar origin. On textural grounds all four were classified as regolith breccias (MASON, 1982; MARVIN, 1983; OSTERTAG and RYDER, 1983; RYDER and OSTERTAG, 1983; YANAI and KOJIMA, 1984; BISCHOFF and STÖFFLER, 1985; YANAI and KOJIMA, 1985a, b; BISCHOFF *et al.*, 1986; YANAI *et al.*, 1986).

The Apollo and Lunar missions sampled only a very limited region of the frontside of the lunar surface. Thus, the investigation of lunar meteorites may in principle provide information of the chemistry and petrology of a larger fraction of the lunar crust. Lunar meteorites are therefore extremely valuable sources of information about the Moon's crust (WARREN and KALLEMEYN, 1986). In particular do we now have the opportunity to study samples from the lunar far side. The ALHA81005 and the Y-791197 lunar materials are both good candidates for far side samples (PALME *et al.*, 1983; OSTERTAG *et al.*, 1986).

Petrographic analyses of the types and frequency of mineral and lithic clasts provide information about the regolith and subregolith basement. Chemical analyses of the bulk samples help to elucidate the chemical composition of the lunar crust at the impact site and noble gas analyses give independent information about the exposure time of the samples on the surface of the parent body.

All studies combined may help to answer the question whether lunar meteorites are pieces of the same fall implying that the ejection of material from the Moon was a single event, or if several impacts on the lunar surface were necessary to explain the occurrence of lunar meteorites in Antarctica.

As done for Y-791197 (OSTERTAG *et al.*, 1986) we have made a combined effort to analyze the petrography and the chemical composition of the lunar meteorite Y-82192. In addition Y-82193 was studied petrographically. We compare these results with those obtained from the studies of the first two lunar meteorites, ALHA81005 and Y-791197.

2. Experimental Techniques and Samples

Polished thin sections Y-82192,50–1 and Y-82193,91–2 and a 97 mg chip Y-82192,75 were available for petrographic studies and chemical analysis. Textural investigations were made with a Zeiss polarizing microscope in combination with a Zeiss Mop Videoplan.

The fine-grained matrix was studied with a Cambridge Scanning Electron Microscope at the Geologisch-Paläontologischen Institut der Universität Münster.

For a bulk chemical analysis a 85.3 mg chip of Y-82192,75 was irradiated in the TRIGA reactor of the Institut für Kernchemie (Universität Mainz) at a neutron flux of 7×10^{11} n/cm^{2}s for several hours. After irradiation it was counted on large Ge(Li) crystals. The γ-spectra obtained were evaluated using the peak-fitting routine of KRUSE (1979).

Three subsamples of several mg were used to determine isotopic compositions of He, Ne, and Ar as well as the concentrations of ^{84}Kr and ^{132}Xe. The experimental procedures were described by WEBER *et al.* (1983).

3. Results and Discussion

3.1. Petrography, shock history and clast population studies

The two lunar meteorites, Y-82192 and -82193 are very similar in texture and mineralogy. Both are polymict breccias consisting of lithic and mineral clasts embed-

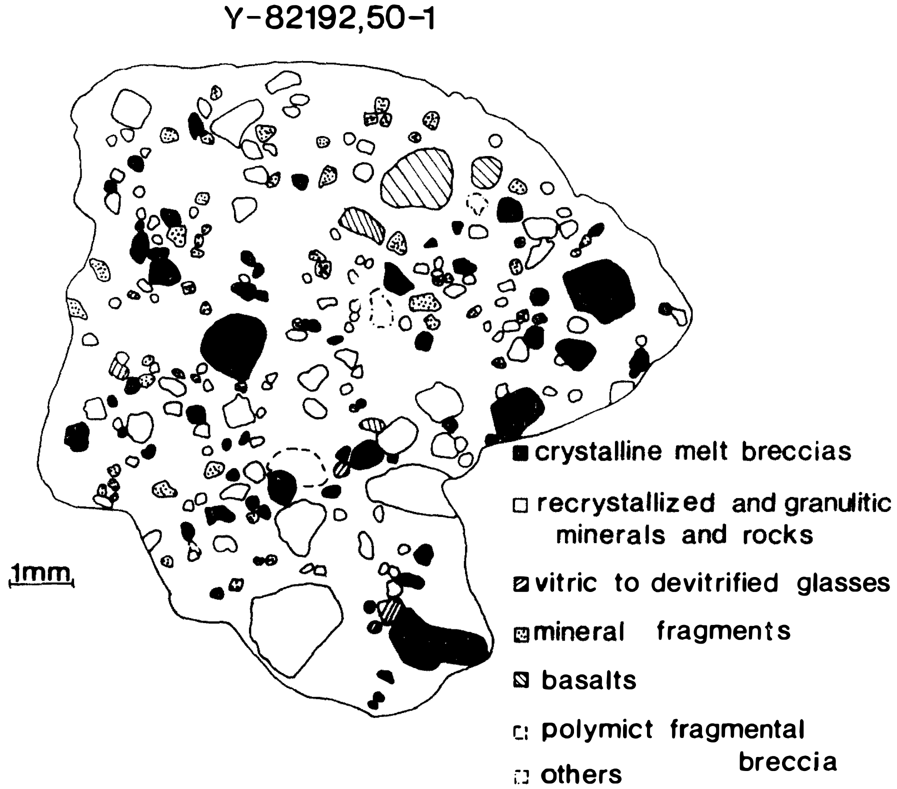


Fig. 1. Sketch map of thin section Y-82192,50-1 showing the distribution of mineral and lithic clasts.

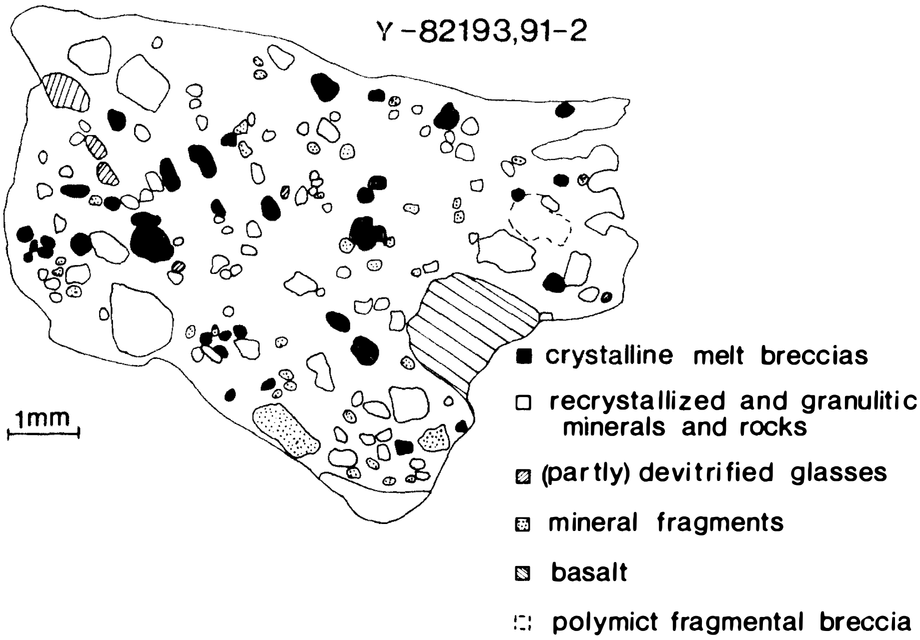


Fig. 2. Sketch map of thin section Y-82193,91-2 showing the distribution of mineral and lithic clasts.

ded in a fine-grained matrix. Figures 1 and 2 are sketch maps of the thin sections demonstrating the distribution of the major lithologies larger than ~0.1 mm. Compared to the previously identified lunar meteorites (ALHA81005, Y-791197) the grain size of mineral and lithic clasts is much smaller. The dominant lithologies are fragments of recrystallized and granulitic rocks and crystalline impact melt breccias. The microscopic study revealed that glasses or devitrified glasses are very rare in contrast to ALHA81005 where abundant irregularly-shaped brown glass layers were observed. Recrystallized glass spherules are extremely rare.

The mineral clasts are angular to subrounded and form an extremely dense matrix whose texture is very similar to terrestrial and lunar sediments shock-lithified at low pressures, *e.g.* <10 GPa (KIEFFER, 1975; SCHAAL and HÖRZ, 1980). Within the matrix small opaque mineral grains were observed mainly located at grain boundaries. Although the matrix is densely compacted a kind of micro-porosity was observed within the matrix and at the edges of large mineral and lithic clasts. It consists of small vugs (<2 μm in size) which are irregularly-shaped, dumb-bell-like or amoeboid, and sometimes arranged in strings. Since they do not exist within large mineral and lithic fragments we suggest that they were formed during the compaction of the regolith to form the regolith breccia. This kind of micro-porosity is often observed within the matrix of breccias from Apollo 16 and also occurs within the fine-grained matrix of the other lunar meteorites. In ALHA81005 this porosity is dominant within the brown glassy materials.

As in all polymict impact breccias, the lithic clasts of both lunar meteorites belong to rather variable shock metamorphic regimes and range from weakly shocked rocks to impact-formed melt lithologies (*e.g.* crystalline melt breccias). It is conspicuous that all clasts of the two meteorites are shocked to some degree; unshocked mineral and lithic clasts are lacking. Based on experimental work on plagioclase it is known that shock effects in plagioclase are sensitive indicators for the estimation of the peak shock pressures (STÖFFLER, 1974; OSTERTAG and STÖFFLER, 1982). All plagioclase fragments show fracturing, undulous extinction or mosaicism. However, diaplectic plagioclase glass (maskelynite) was never observed within Y-82192 and -82193. Significant amounts of plagioclase will be transformed to maskelynite in non-coherent, porous materials already at 20 GPa (GIBBONS *et al.*, 1975; SCHAAL and HÖRZ, 1980). Consequently, all mineral and lithic clasts now observed within Y-82192 and -82193 had suffered a maximum shock pressure below 20 GPa during or after the lithification process.

Loose regolith materials are consolidated under shock pressures well below 4 GPa (BISCHOFF and LANGE, 1984). Incipient formation of intergranular melts in porous regolith requires shock pressures between 10 and 20 GPa (KIEFFER, 1975; GIBBONS *et al.*, 1975; SCHAAL *et al.*, 1979; SCHAAL and HÖRZ, 1980).

Optical and electron microscopical studies demonstrated the absence of significant amounts of intergranular melts in the analyzed lunar meteorites Y-82192 and -82193. However, we cannot rule out that some local melts were formed submicroscopically at grain contacts, as found within the clastic matrices of consolidated chondritic breccias (BISCHOFF *et al.*, 1983). Therefore, we believe that these lunar meteorites suffered peak shock pressures in the order of 10 GPa during the consolidation event.

Since maskelynite is not present, the studied samples have not suffered shock pressures in excess of 20 GPa during the impact event that caused ejection of these meteorites (or of a single body) from the Moon. Many plagioclase grains are recrystallized and all glasses are devitrified. The annealing process most probably took place before the incorporation of the fragments into the regolith, thus, before the lithification process.

The frequency distribution of mineral and lithic clasts within Y-82192 and -82193 gives important information about the nature of the regolith and sub-regolith basement at the impact site of these samples. As done for ALHA81005 (BISCHOFF and STÖFFLER, 1984) and Y-791197 (BISCHOFF and STÖFFLER, 1985; OSTERTAG *et al.*, 1986) we have determined the clast population statistics of the thin sections Y-82192,50–1 and -82193,91–2. Note that OSTERTAG *et al.* (1986) used some other classification criteria and classified the fine-grained, dark brown, mafic-rich crystalline melt breccia of BISCHOFF and STÖFFLER (1985) as a recrystallized polymict fragmental breccia (mafic-rich).

Table 1. Clast population in the lunar meteorites Yamato-82192 and -82193; clasts ≳0.1 mm (BISCHOFF et al., 1986).

Type of rock		Y-82192			Y-82193	
	No.	area mm^2	vol %	No.	area mm^2	vol %
Granulitic anorthosite	7	1.72	7.9	10	0.52	6.0
Granulitic (gabbroic, noritic) anorthosite	2	0.14	0.7	2	0.91	10.5
Intragranularly recrys. catacl. anorthosite	13	1.89	8.9	23	1.36	15.6
Intragranularly recrystallized plagioclase	87	4.04	19.1	45	1.02	11.7
Recrystallized feldspathic melt breccia	2	2.62	12.4	1	0.05	0.6
Recrystallized feldspathic rocks and breccias, and granulitic lithologies	111	10.41	49.0	81	3.86	44.4
Feldspathic fine-grained to microporphyritic CMB } feldspathic	33	2.47	11.7	27	1.13	13.0
Feldspathic, subophitic CMB } feldspathic	1	0.54	2.6			
Micropoikilitic CMB } mafic	1	0.20	0.9			
Fine-grained, mafic-rich CMB } mafic	12	1.44	6.8	5	0.07	0.8
Fine-grained, subophitic CMB } mafic	11	1.17	5.5	5	0.30	3.5
Crystalline melt breccias	58	5.82	27.5	37	1.40	17.3
Devitrified glass spherules	1	0.01	0.1	1	0.02	0.2
(Partly) devitrified impact glass	4	0.31	1.5	4	0.36	4.1
Impact melt with variolitic texture				1	0.02	0.2
Devitrified (impact) glasses	5	0.32	1.6	6	0.40	4.5
Plagioclase mineral fragments	45	1.82	8.6	27	0.82	9.4
Mafic mineral fragments	11	0.31	1.5	7	0.10	1.1
Mineral fragments	56	2.13	10.1	34	0.92	10.5
Feldspathic and mafic basalts	4	1.66	7.8	1	1.67	19.2
Cataclastic gabbro	1	0.22	1.0			
Quenched spinel-troctolite	1	0.03	0.2			
Polymict fragmental breccia	1	0.45	2.1	1	0.35	4.0
Others	2	0.13	0.6			
All others	13	2.49	11.7	2	2.02	23.2
Total	239	21.17	99.9	158	8.70	99.9

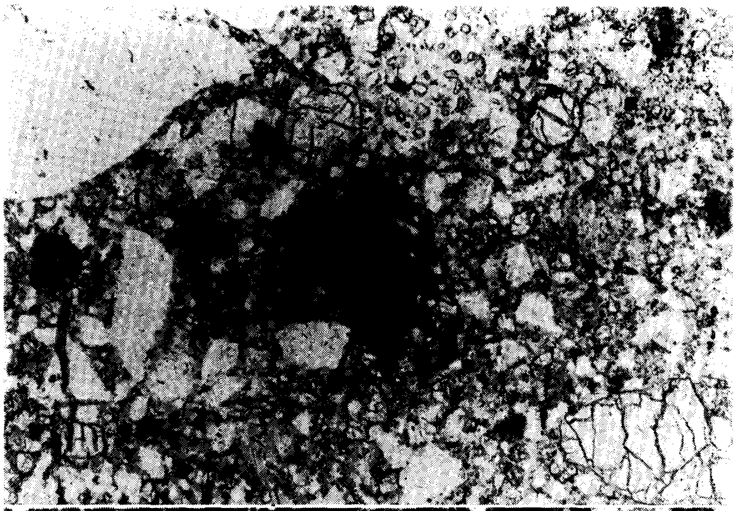
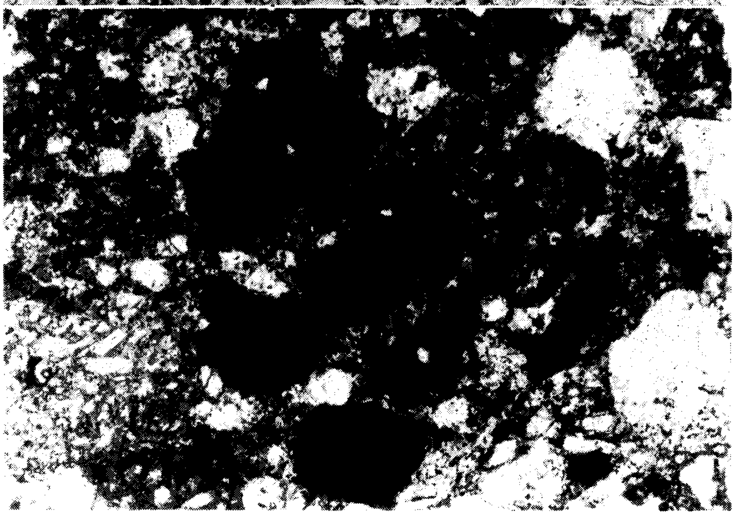


Fig. 3. Crystalline impact melt breccias (dark gray) are embedded in a very fine-grained, densely-compacted matrix.
a. Y-82192; one polarizer, width 0.8 mm.



b. Y-82193; one polarizer, width 1.2 mm.

Table 2. Clast population in lunar meteorites; data in vol % (BISCHOFF et al., 1986).

	Y-82192	Y-82193	Y-791197	ALHA81005
Recystallized and granulitic lithologies	49.0	44.4	53.9	56.5
Feldspathic crystalline melt breccias	14.3	13.0	12.7	6.5
Mafic crystalline melt breccias	13.2	4.3	10.9	15.7
Vitric to devitrified (impact) glasses	1.6	4.5	6.5	11.0
(Vitric impact glasses)	—	—	(0.4)	(1.5)
Mineral fragments	10.1	10.5	4.1	2.1
Feldspathic and mafic basalts	7.8	19.2	—	—
Polymict fragmental breccias	2.1	4.0	11.5	7.4
Others	1.8	—	0.4	1.0
Total	99.9	99.9	100.0	100.2

The thin sections Y-82192,50–1 and -82193,91–2 contain about 26.4 and 24.7 vol%, respectively, of mineral and lithic clasts larger than ~0.1 mm. In ALHA81005 and Y-791197 we classified about 30 vol% as clasts; thus, the matrices of Y-82192 and -82193 appear to be finer-grained compared to the previous two lunar meteorites.

In Y-82192 239 and in Y-82193 158 mineral and lithic clasts were mapped (BISCHOFF *et al.*, 1986) and classified according to the classification for lunar highland rocks

(STÖFFLER *et al.*, 1980). The results of this clast population study are given in Table 1. Recrystallized plagioclases, and recrystallized feldspathic rocks and breccias, and granulitic lithologies are by far the dominant rock types with 44.4 vol% (Y-82193) and 49.0 vol% (Y-82192). These values are somewhat lower than those obtained for the other lunar meteorites (Y-791197: 53.9 vol%; ALHA81005: 56.5 vol%).

Intragranularly recrystallized cataclastic anorthosites and plagioclases and granulitic anorthosites are abundant in both rocks, Y-82192 and -82193, while additionally, two large granulitic (noritic, gabbroic) anorthosites occur in Y-82193 (10.5 vol%), and some large recrystallized feldspathic melt breccias in Y-82192 (12.4 vol%).

Crystalline melt breccias (CMBs) are common in both samples (Fig. 3). Mafic crystalline melt breccias are slightly more abundant in thin section Y-82192,50–1; however, in both samples more feldspathic crystalline melt breccias were mapped compared to the mafic ones. The same result was obtained by a study of the frequency distribution of clasts from Y-791197, in contrast to ALHA81005 where the mafic crystalline melt breccias dominate (Table 2). In all four lunar meteorites the total abundances of crystalline melt breccias are similar (17.3–27.5 vol% of the mapped clasts), *e.g.* 4.3–7.6 vol% of the entire rock. The feldspathic crystalline melt breccias are mainly fine-grained to microporphyritic (Fig. 4) and different from those within Apollo 16 fragmental breccias where all microporphyritic melt breccias have a coarser-grained crystalline matrix. In Y-82192 a feldspathic CMB with a subophitic texture was observed. Most mafic CMBs are either fine-grained subophitic (Fig. 5), as observed in many breccias from the Apollo samples, or fine-grained to microporphyritic, mafic-rich (Fig. 4). In contrast to the feldspathic fine-grained to microporphyritic crystalline melt breccias this mafic variety has abundant mafic mineral fragments and large amounts of mafic material in the fine-grained mesostasis (Fig. 4).

Significant differences between ALHA81005, Y-791197, Y-82192, and Y-82193 exist concerning the glass content. In ALHA81005 11 vol% (1.5 vol% vitric impact glass) and in Y-791197 6.5 vol% vitric to devitrified glasses (0.4 vol% vitric impact glass) were mapped. In Y-82192 and -82193 vitric impact glasses are missing and the amount of (partly) devitrified glasses is extremely low (1.6 and 4.5 vol%, respectively).

In ALHA81005 irregularly-shaped brown bodies of impact glasses are a characteristic lithology (BISCHOFF and STÖFFLER, 1984). Since Y-82192 and -82193 do not contain this component we can rule out (already at this point) that ALHA81005 and these Yamato samples are derived from the same rock. Both thin sections, Y-82192, 50–1 and Y-82193,91–2 contain one recrystallized spherule each (Fig. 6). In the other lunar meteorites several glassy spherules were observed. Based on the low abundance of spherules and the absence of glasses we state that Y-82192 and -82193 have less regolith components than the other lunar meteorites.

In both samples (Y-82192, -82193) about 10 vol% mineral fragments were recorded. Mineral fragments appear to be more abundant than in the previous lunar meteorites. This result may be caused by the following mechanism: The regolith at the impact site was more heavily fragmented; thus, it contained higher abundances of mineral clasts from broken basement rocks. This suggestion is supported by a lower percentage of clasts >0.1 mm in the thin sections of Y-82192 and -82193 (24–26 vol%) compared to ALHA81005 and Y-791197 (30–32 vol%) and by the fact that also 12–

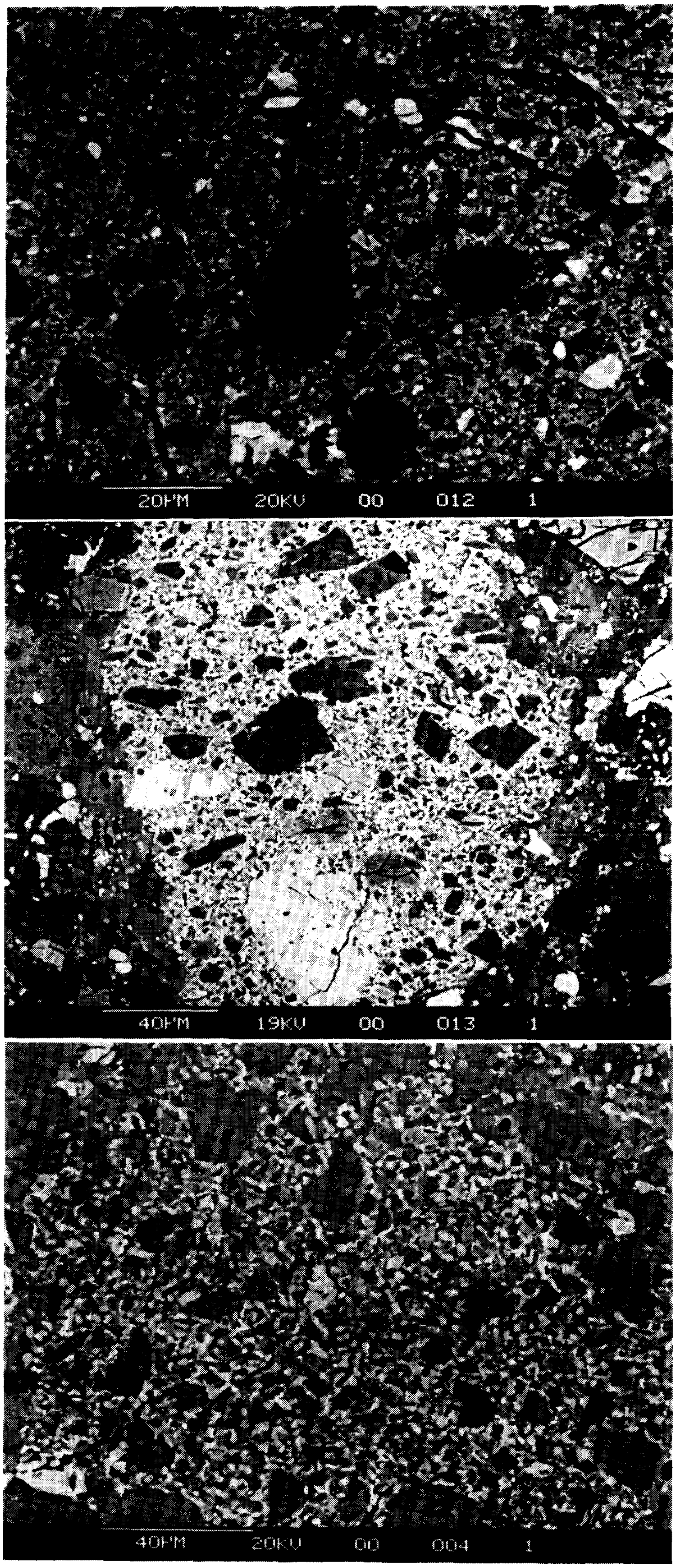


Fig. 4. Crystalline impact melt breccias: plagioclase (dark gray), olivine and pyroxene (light gray).

a. Feldspathic fine-grained to microporphyritic impact melt breccia from Y-82192; image in backscattered electrons.

b. Fine-grained, mafic-rich impact melt breccia from Y-82192; image in backscattered electrons.

c. Fine-grained, mafic-rich impact melt breccia from Y-82193; image in backscattered electrons.

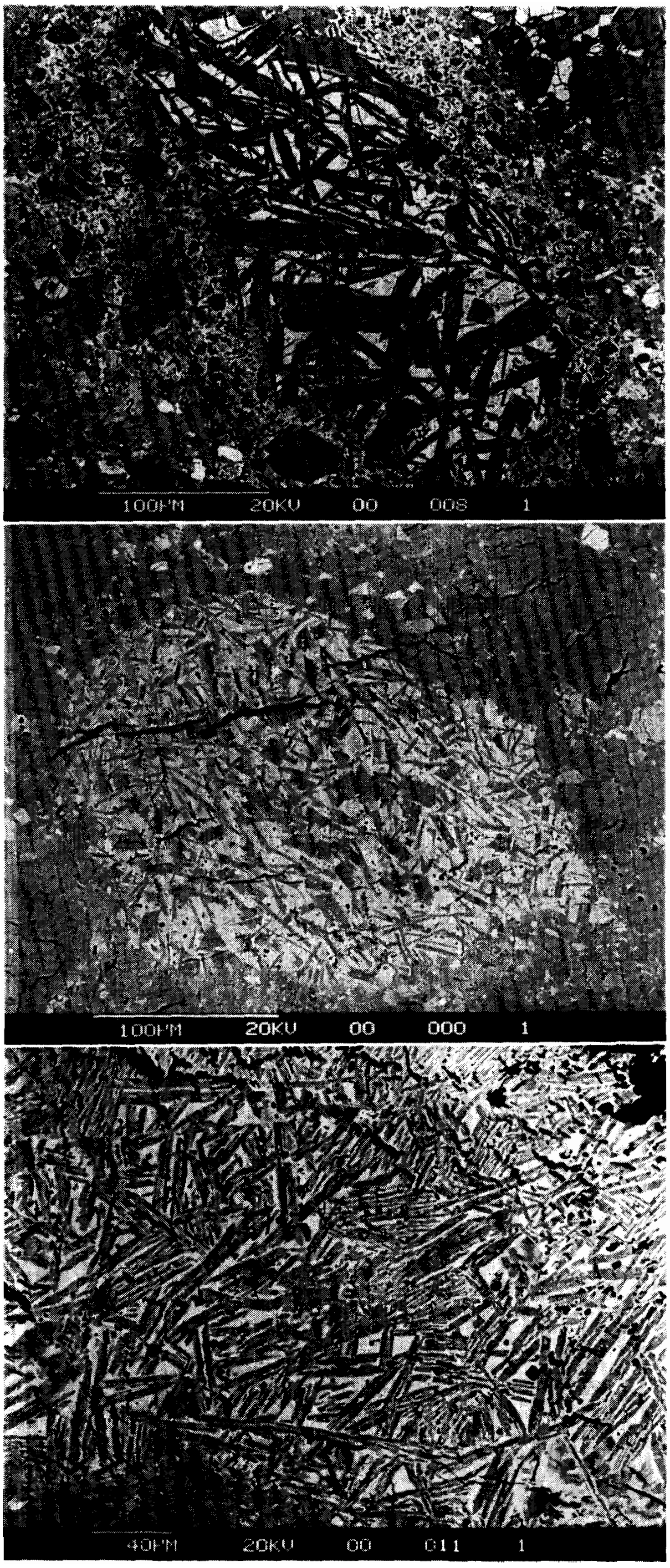


Fig. 5. Crystalline impact melt breccias: plagioclase (dark gray), mafic minerals (light gray); images in backscattered electrons.

a. Fine-grained subophitic impact melt breccia with abundant plagioclase from Y-82193.

b. Fine-grained subophitic impact melt breccia with abundant pyroxene from Y-82193.

c. Fine-grained impact melt breccia with a subophitic to variolitic texture from Y-82192.

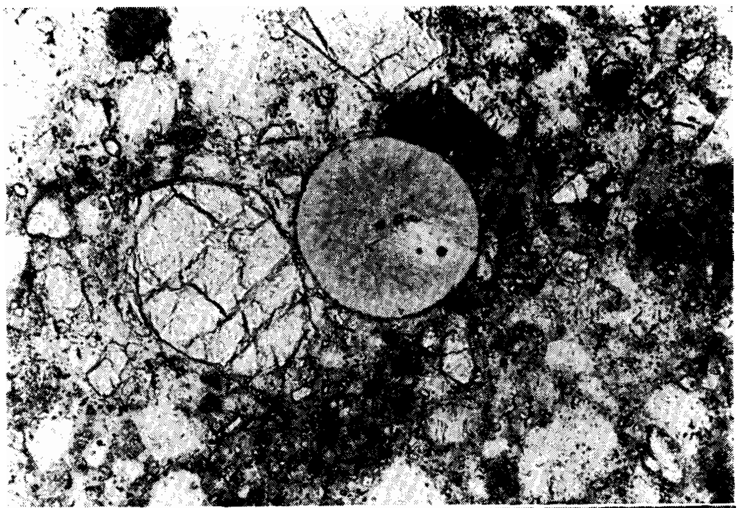


Fig. 6a. Y-82192: a recrystallized spherule (~130 μm in apparent diameter is embedded in a fine-grained matrix; one polarizer.

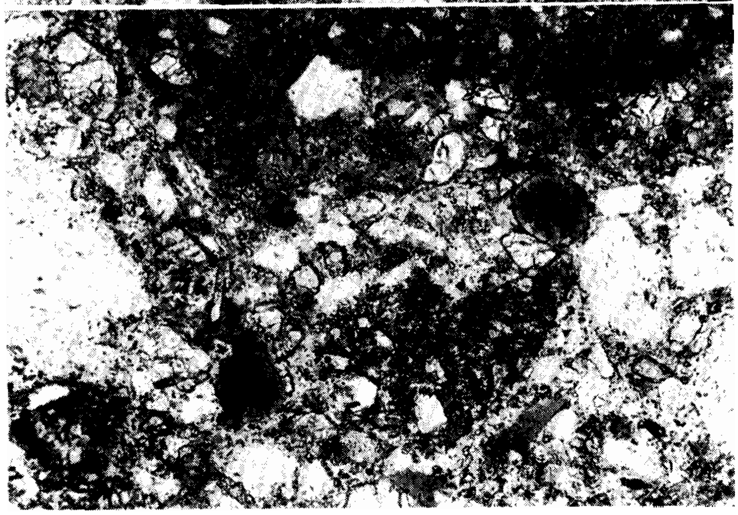


Fig. 6b. Y-82193: a small recrystallized spherule (~100 μm in apparent diameter) and a devitrified impact glass (lower left); one polarizer.

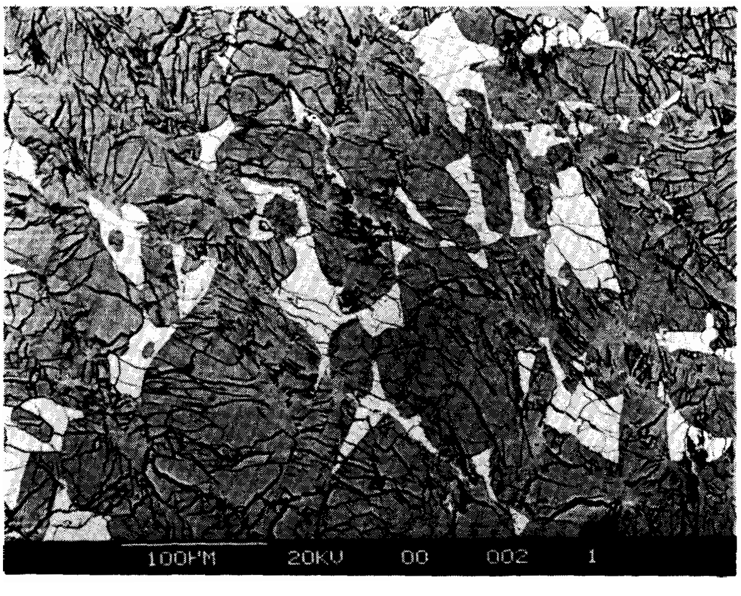


Fig. 7. Microstructure of a basaltic clast in Y-82193 consisting of pyroxene (light) and plagioclase (dark gray). Image in backscattered electrons.

19 vol% intragranularly recrystallized plagioclase grains were mapped in contrast to only 3.3 vol% in Y-791197 and 4.8 vol% in ALHA81005 (BISCHOFF and STÖFFLER, 1984, 1985).

In contrast to ALHA81005 and Y-791197, Y-82192 and Y-82193 contain basaltic clasts (Fig. 7). In Y-82192 four clasts and in Y-82193 a single clast contribute 7.8 and 19.2 vol%, respectively, to the clast distribution. The high volumetric abundances of basalts also support the suggestion that these lunar meteorites are derived from other rocks than ALHA81005 and Y-791197. Other (minor) types of lithic clasts are listed in Table 1.

In conclusion, we believe that the two lunar meteorites are shocked fragmental breccias in which a genuine regolith component is subordinate. The protolith of the breccias is the subregolith basement which consists of feldspar-rich fragmental breccias of highland composition. The two lunar meteorites are texturally similar to the fragmental breccias exposed by the North Ray Crater at Apollo 16 (STÖFFLER *et al.*, 1985).

3.2. Bulk chemistry of Y-82192

The results of INAA are given in Table 3, along with data from Y-791197 and ALHA81005 for comparison (OSTERTAG *et al.*, 1986; PALME *et al.*, 1983). The major and minor element composition of Y-82192 is very similar to that of Y-791197 and not too different from ALHA81005. In particular, ratios such as Fe/Mn, Fe/Sc, K/La, Na/Eu *etc.* are in the range of typical lunar ratios (Table 4). The same arguments that have been used to prove that Y-791197 and ALHA81005 are lunar meteorites can be applied to Y-82192. There is a tendency that Y-82192 and -791197 have somewhat higher concentrations of Cr, V, and Sc than ALHA81005 (Table 3), with an opposite trend for Mg.

However, the major difference in the composition of Y-82192 when compared to the othcr lunar meteorites is the low contents of incompatible elements. In Fig. 8 we have plotted CI-normalized REE-patterns for a variety of lunar rocks including the three lunar meteorites. Clearly, Y-82192 has a factor of two lower contents of light REE than ALHA81005 and is a factor of three lower than Y-791197. The difference in heavy REE is somewhat less, due to the peculiar pattern of Y-82192. The low REE content of Y-82192 can be extended to other incompatible elements, such as Hf and the non-refractory incompatible K. The different signature in incompatible elements clearly distinguishes Y-82192 from the other lunar meteorites and implies a different source region for this meteorite.

It is very remarkable that the low incompatible-element content of Y-82192 is not accompanied by a corresponding change in major or minor elements. The Fe/Mg ratio in this meteorite is higher, not lower as expected from an igneous fractionation trend. Similarly, the Cr-content of Y-82192 is the same as that of Y-791197, despite a threefold higher LREE content in the latter meteorite.

Incompatible elements are obviously decoupled from major elements. This is a common observation in lunar highland rocks. However, in most cases does the contaminant have a KREEP pattern with its typical LREE-enrichment. This ubiquitous highland component can be seen in Fig. 8 from samples of the Apollo 14, 15, 16, and 17 landing sites. All samples with higher absolute REE contents than 67955

Table 3. Concentration of major, minor and trace elements in Yamato-82192 compared to ALHA-81005 (PALME et al., 1983) and Y-791197 (OSTERTAG et al., 1986).

%	Y-82192 85.29 mg	Error %	Y-791197 59.3 mg	Error %	ALHA81005 128 mg	Error %
Mg	3.47	10	4.25	5	4.78	5
Al	13.53	3	13.30	3	13.4	3
Ca	10.6	6	11.4	5	10.80	3
Ti	0.25	10	0.22	10	0.14	10
Fe	4.74	3	5.05	3	4.20	3
ppm						
Na	2650	3	2410	3	2250	3
P			100	30	90	25
K	150	17	290	5	230	5
Sc	14.5	3	16.5	3	9.24	3
V	41	5	39	10	26	8
Cr	1020	3	1034	3	862	3
Mn	657	3	734	3	587	3
Co	19.9	4	16.9	3	20.2	3
Ni	120	10	100	15	186	5
Zn	30	15	50	20	18	2
Ga	3.78	11	9.87	5	2.8	5
As	<0.2					
Se	<0.2				0.6	
Br	<0.2					
Rb	<3				<1.5	
Sr	136	15	118	20	128	10
Zr					30	15
Sb	<0.1					
Cs	<0.1					
Ba	21	20	34	25	34	20
La	1.13	4	3.24	4	2.44	3
Ce	2.98	6	8.76	8	6.9	5
Nd	1.97	11	5.24	10	3.9	10
Sm	0.631	4	1.56	4	1.18	3
Eu	0.754	3	0.723	3	0.704	3
Gd					1.4	20
Tb	0.17	12	0.33	10	0.27	5
Dy	1.13	5	2.22	5	1.7	10
Ho	0.26	10	0.48	10	0.37	15
Tm			0.23	20	0.18	20
Yb	0.76	5	1.34	4	1.06	5
Lu	0.115	4	0.19	4	0.15	3
Hf	0.44	6	1.11	5	0.92	3
Ta			0.16	8	0.12	8
Ir	0.0056	13	0.0059	15	0.0073	10
Au	0.0011	15	0.0013	15	0.0021	7
Th	0.2	20	0.43	15	0.35	8
U	0.05	20	0.14	15	0.103	15

have a parallel pattern of REE. Granulites such as 67955 or 78155 and the ALHA81005 meteorite have a slightly different pattern, although the LREE are still parallel to the KREEP pattern. Since the KREEP component was probably distributed by impacts

Table 4. Element ratios in lunar meteorites and lunar highland rocks.

	Y-82192 (1)	Y-791197 (2)	ALHA81005 (3)	Average lunar highlands (4)
Fe/Mn*	69.5	66.8	66.8	70
Fe/Sc*	3145	2970	4240	4000
Mg/Cr	34.0	41.1	55.4	57
Al/Ga	35800	13500**	38600	36000
K/La***	133	89.5	94.3	70
Na/Eu	3515	3333	3196	3000

* Meteoritic Fe substracted (Fe-15 Ni); ** Ga-excess in this sample (see BISCHOFF and PALME, 1986); *** Highland rocks low in incompatible elements have somewhat higher K/La ratios, because of K in plagioclase.

(1) this work; (2) OSTERTAG *et al.* (1986); (3) PALME *et al.* (1983); (4) WÄNKE *et al.* (1975).

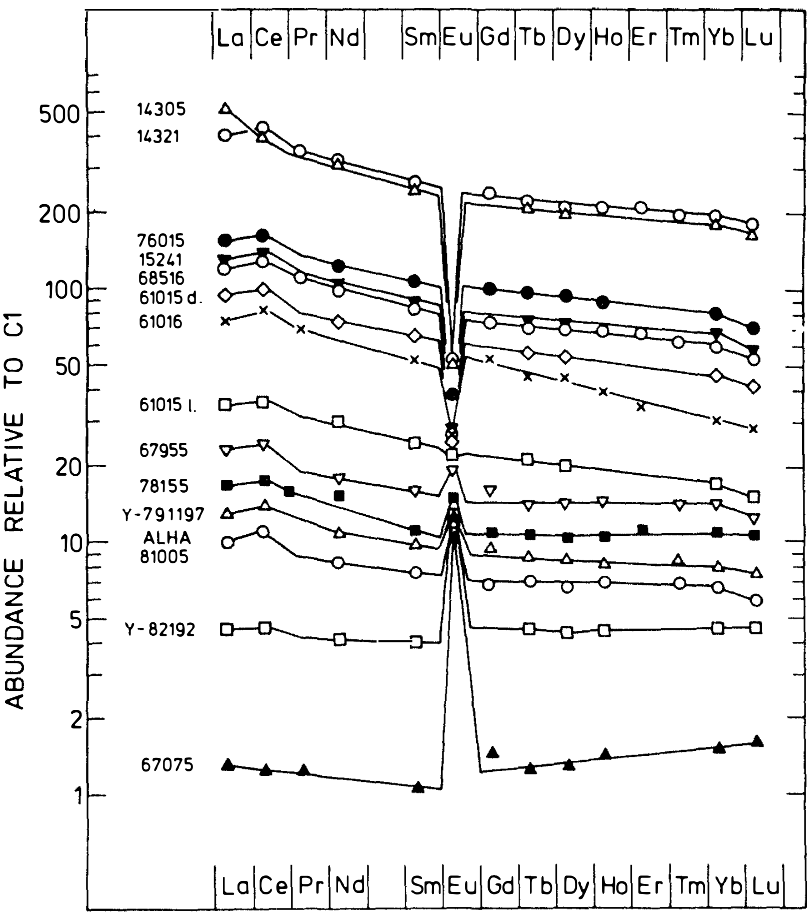


Fig. 8. CI-normalized REE-abundances of lunar highland samples and three lunar meteorites. The parallel patterns of Apollo 14, 16, and 17 rocks are due to the presence of a KREEP component. The patterns for 67955, 78155, and ALHA81005 are slightly different with their flat HREE. Y-791197 could have a small amount of KREEP. But in Y-82192 the KREEP component is completely lacking. Data for ALHA81005 and Y-791197 from PALME *et al. (1983) and* OSTERTAG *et al. (1986). Data for lunar highland rocks are from the Mainz laboratory.*

over the surface of the Moon, it is possible that the Y-791197 has still a small fraction of this component, while Y-82192 is essentially free of it. The flat HREE pattern of ALHA81005 requires however another component. From Fig. 8 it is apparent that the ALHA lunar meteorite has a pattern similar to 67955 and 78155, two lunar granulites (see PALME *et al.*, 1983).

Since the rare gas content of Y-82192 is significantly below that of other regolith-breccias, we suspect that Y-82192 comes from a stratigraphic position where it was never exposed to solar wind (see following section). The absence of KREEP could be explained in the same way, assuming that the KREEP-component was added by mechanical mixing of materials distributed through impacts. If this interpretation is correct one could find a correlation between incompatible elements and the rare gas content in various fractions of the meteorite.

Despite similar Al and Ca contents of the three lunar meteorites (Table 3), reflecting similar modal abundances of plagioclase, there is a distinct increase in Eu, Sr, and Na from ALHA81005, through Y-791197 to Y-82192. This indicates some variability in the composition of the plagioclase. The plagioclase component as a result of the early lunar differentiation has been found to be variable in composition on the present lunar surface (see for example PALME *et al.*, 1984)

The abundances of volatile and moderately volatile elements in Y-82192 are typical for lunar highland rocks and are in the same range as for ALHA81005. In particular do we not find any enrichments of Ga and Zn that were detected in some subsamples of Y-791197 (BISCHOFF and PALME, 1986).

Siderophile element contents in Y-82192 are very similar in an absolute and in a relative sense when compared to the other lunar meteorites. The basically chondritic ratios among Ni, Ir, Au, and Co (corrected for indigenous Co) in all lunar meteorites (OSTERTAG *et al.*, 1986; PALME *et al.*, 1983) may indicate the addition of a late meteoritic component, that was added to the Moon after the plagioclase-rich clast had been formed. The level of Ir in these rocks is in the same range as in the upper mantle of the Earth (JAGOUTZ *et al.*, 1979). It is therefore tempting to speculate that this very late meteoritic component is visible not only in lunar highland rocks but also in terrestrial upper mantle rocks.

3.3. *Noble gases*

Since the low contents of solar wind gases observed in the first two analyses turned out to be rather unexpected (WEBER *et al.*, 1986) we felt it important to make sure that sample mix-up can be excluded with certainty. To this end a 3.61 mg chip, which had been part of the 85.29 mg used for neutron activation analysis, was re-irradiated and its chemical composition compared with that of the large sample of which it had been part during the first irradiation. Not all elements could be measured after the second irradiation, but those which could (among them the important diagnostic elements Ca, Fe, Sc, Mn, La, Sm, Eu) all agreed within 15% with those in the large sample. The dose of thermal neutrons received during the two irradiations was 3×10^{16} cm^{-2} which does not affect the abundance of any of the isotopes of He, Ne, and Ar in any significant way.

This chip was degassed in three temperature steps, with 1 h each at *ca.* 600° and

Table 5. Nobel gas contents of subsamples from Y-82192. All concentrations are given in units of 10^{-8} cm^3STP/g. Uncertainties in isotope ratios are ±3%; nuclide abundances are accurate to better than 6% for He, Ne and Ar and to better than 25% for Kr and Xe. Differences larger than these values between the two specimens are ascribed to sample heterogeneity.

Weight [mg]	Extraction temp.	^{3}He	^{4}He/^{3}He	^{21}Ne	^{22}Ne/^{21}Ne	^{20}Ne/^{21}Ne	^{38}Ar	^{36}Ar/^{38}Ar	^{40}Ar/^{36}Ar	$^{38}Ar_{sp}$	^{84}Kr	^{132}Xe
2.95	1600°C	7.03	6.36	2.44	1.35	2.21	3.28	2.30	112	2.12	0.020	0.0027
7.44	1600°C	5.69	5.75	2.28	1.33	1.70	2.69	1.72	153	2.07	0.017	0.0018
3.61	600°C	1.90	6.74	0.635	1.27	1.06	0.081	1.10	< 34	0.073	—	—
	800°C	2.47	7.98	0.754	1.25	1.06	0.484	0.72	23	0.477	—	—
	1600°C	0.66	8.62	0.751	1.38	3.63	1.91	1.28	184	1.65	—	—
	Total	5.03	7.59	2.14	1.30	1.96	2.48	1.16	158	2.20	—	—
Mean		5.92	6.51	2.29	—	—	—	—	—	2.13	0.018	0.0022

Table 6. Nobelgas contents of three lunar meteorites, all regolith breccias. Concentrations are given in $10^{-8}cm^3STP/g$. In ALHA81005 and Y-791197 more than 99% of total ^{4}He, ^{20}Ne, and ^{36}Ar are of trapped origin. The upper limit for trapped ^{4}He in Y-82192 includes the total radiogenic ^{4}He; it is derived by assuming the ratio of cosmogenic ^{4}He/^{3}He to be 5.0.

Meteorite	^{4}He	^{4}He/^{3}He	^{20}Ne	^{20}Ne/^{22}Ne	^{22}Ne/^{21}Ne	^{36}Ar	^{36}Ar/^{38}Ar	^{40}Ar/^{36}Ar	^{84}Kr	^{132}Xe	Reference
ALHA81005	440000	2600	50000	12.5	24.9	15750	5.29	1.80	6.12	1.16	(1)
	616000	2680	55900	12.5	24.6	19520	5.24	1.72	9.94	1.15	(2)
Y-791197	450000	2240	94700	12.4	24.6	34800	5.32	2.56	17.3	2.45	(3)
	453000	2560	97500	12.4	26.1	36600	5.30	2.58	22	2.5	(4)
Y-82192											
Total	38.5	6.51	4.49	1.47	1.33	5.02	1.78	133	0.018	0.0022	
Trapped	≤9	—	2.5	—	—	3.6	—	—	0.018	0.0022	

(1) BOGARD and JOHNSON (1983); (2) EUGSTER *et al.* (1986); (3) TAKAOKA (1986); (4) OSTERTAG *et al.* (1986).

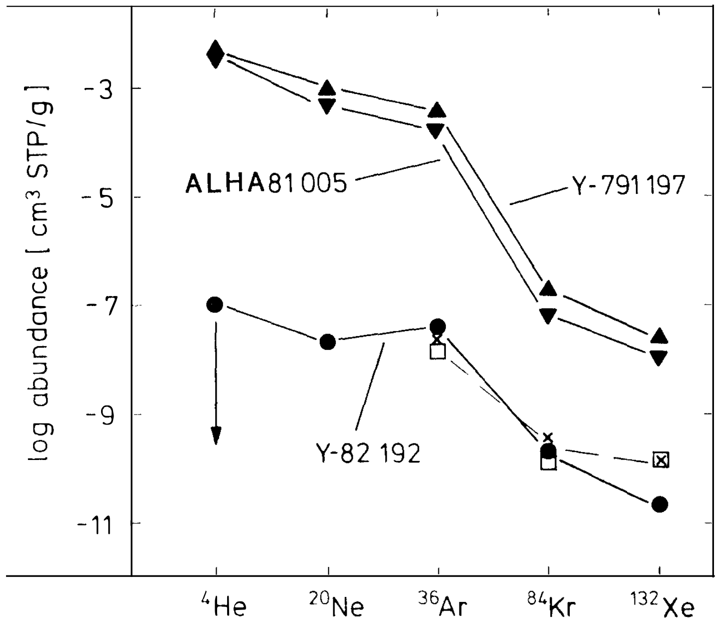


Fig. 9. Nuclide abundance patterns of trapped noble gases in three lunar meteorites. In Y-791197 and ALHA81005 the abundances of all nuclides except He are very similar to those in the lunar regolith. (In the present plot Y-791197 and lunar regolith would be indistinguishable except for ^{4}He which is about 7 times higher in the regolith (TAKAOKA, 1986). Y-82192, on the other hand, is much more similar to normal chondrites of high petrologic grade (□) and to the Apollo XVII boulder (shown are the results (×) for the anorthositic breccia (LEICH et al., 1975).

800°C and 30 min at 1600°C. All experimental data are listed in Table 5. The most striking result is that the concentrations in Y-82192 of all noble gases are entirely different from those of the previously analyzed two lunar meteorites. It is obvious from Table 6 and Fig. 9 that in Y-791197 and ALHA81005 the trapped gases are very much the same as they have been observed in the lunar regolith proper. In Y-82192, however, trapped ^{4}He and ^{20}Ne are lower by at least four orders of magnitude. For the trapped heavy gases (^{36}Ar, ^{84}Kr, and ^{132}Xe) the difference is not quite that large but they, too, are more than 100 times less abundant in Y-82192 than in authentic lunar regolith and in Y-791197 and ALHA81005. Indeed, gas concentrations as well as isotope and nuclide abundance ratios of the light noble gases in Y-82192 are so much like those typically encountered in Ca-rich achondrites that, based on these data, one would never have suspected a lunar origin for Y-82192. This is in agreement with the petrographic interpretation of the two meteorites as subregolith polymict fragmental breccias.

Cosmogenic ^{3}He, ^{21}Ne, and ^{38}Ar are present in a ratio 2.8 : 1.1 : 1. With the chemical data from Table 3 the production ratio P(^{21}Ne)/P(^{38}Ar) is predicted to be 1.36, if we use the relations derived for eucrites (SCHULTZ and FREUNDEL, 1985; FREUNDEL *et al.*, 1986), and to fall between 1.10 and 0.72, if irradiation took place on the lunar surface (HOHENBERG *et al.*, 1978). It is not clear at present whether this difference in the predicted ratio is significant in that it reflects the difference is irradiation conditions between meteorites and the lunar surface or whether it is an artefact introduced by uncertainties in the elemental production rates. The conclusion appears to be safe, however, that but little ^{21}Ne can have been lost from Y-82192 by diffusion.

A minimum value for the cosmic ray exposure age is obtained if we use the production rates P(^{21}Ne)=0.236×10^{-8} cm^{-3} STP/g Ma (SCHULTZ and FREUNDEL, 1985) and P(^{38}Ar)=0.175×10^{-8} cm^{3} STP/g Ma (FREUNDEL *et al.*, 1986) as they pertain to meteoritic irradiation conditions. In this case the ^{21}Ne exposure age turns out to be 9.7 Ma and that derived from ^{38}Ar to be 12.2 Ma. If irradiation had taken place on the moon the production rates and, consequently, the time of exposure to the cosmic radiation depend on how deep Y-82192 was buried during the irradiation. The ^{22}Ne/^{21}Ne ratio which, in the case of H- and L-chondrites, is used to derive the degree of shielding cannot be utilized in the present case because of the completely different chemical composition of Y-82192. The ratio P(^{21}Ne)/P(^{38}Ar) is predicted to vary slightly with the amount of shielding (HOHENBERG *et al.*, 1978) but it depends more critically on chemical composition so that we feel that no reliable information can be gained from it. It is to be hoped that shielding depth indicators like ^{131}Xe/^{126}Xe will allow to answer this question. We wish to emphasize, however, that the minimum exposure age derived here is at the same time the maximum period Y-82192 can have been in transit between Moon and Earth.

While the relative amounts of ^{21}Ne and ^{38}Ar are approximately as anticipated there is a clear deficit of ^{3}He. From HEYMANN *et al.* (1968) and the chemical composition of Y-82192 we deduce a production ratio P(^{3}He)/P(^{21}Ne)=8.9. Since the measured ratio is 2.58 it appears that *ca.* 70% of spallogenic He have been lost. For radiogenic He the losses have been still more severe. Even the total ^{4}He present amounts to less than 1% of the expected radiogenic ^{4}He. From this we conclude that the losses occurred at or until a time when not all of the cosmogenic He had yet been produced. We can think of two simple explanations, one requiring a single thermal spike and the other a somewhat more contrived thermal history.

In the single-spike model Y-82192 had about 70% of its spallation products produced when a thermal event led to a complete loss by diffusion of all radiogenic and spallogenic He accumulated until then. From then on the meteoroid stayed sufficiently cool to retain all gases produced. This case is perhaps most easily realized for a two-stage exposure history where 70% of the spallogenic nuclides were produced during the first stage and where the heating event was associated with the removal of the meteoroid from its parent body or with the break-up of a larger proto-meteoroid. This break-up or the separation from the parent body would then have occurred *ca.* 3 Ma ago. The other simple explanation would be that exposure to the cosmic radiation of Y-82192 started after it was excavated from its parent body at which time a thermal peak led to an essentially complete loss of radiogenic ^{4}He. The meteoroid was thrown into such an orbit that it stayed sufficiently warm for 70% of the spallogenic He to be lost or it suffered another thermal peak late in its exposure history which removed part or all of the spallogenic He accumulated until then. This amounts essentially to the classical single-stage exposure concept where a last-minute heating may have occurred during passage of the meteoroid through the terrestrial atmosphere.

The concentration of ^{40}Ar varies between 455 and 845×10^{-8} cm^{3} STP/g. Considering the small sample size it appears possible that at least part of the scatter is due to a non-uniform distribution of potassium. Using the mean ^{40}Ar content of 670×10^{-8} cm^{3} STP/g and the potassium concentration of 150 ppm a found for a much larger sample (Table 3) yields a bulk Ar-K gas retention age of 3600 Ma. Thus, radiogenic ^{40}Ar is much less affected by diffusive gas losses than is radiogenic ^{4}He. This finding is in accord with the results of the step-wise heating experiment which shows that 85% of the total ^{4}He but only 2% or so of ^{40}Ar are released in the first two temperature steps. It is interesting to note that, in this respect, the trapped gases follow radiogenic ^{40}Ar but that the spallogenic gases do not. This is clearly not a property of the diffusing species but rather one of the host phases since 25% of spallogenic ^{38}Ar are given off at or below 800°C already. It appears then that potassium—the radioactive precursor of ^{40}Ar—and trapped gases are residing in very retentive phases but that 25% of Ca—the target element for the production of spallogenic ^{38}Ar—occurs in phases which release their gases at much lower temperatures already. It, furthermore, appears that these phases are essentially free from trapped gases.

It is conceivable that the different release patterns of spallogenic Ar and trapped or radiogenic Ar simply follow from the fact that spallogenic Ar in all probability has been produced very late in the history of Y-82192 while the trapping of gases may be, and the production of most radiogenic Ar certainly is, a very ancient feature. In other words, it is possible that the low-retentivity phases do contain K and did contain trapped gases. Since such phases amount to only about 25% of the total mass, however, we do not think it possible that loss of trapped gases from them is the reason for the extremely low content of primordial gases of Y-82192 as a whole. We rather suggest that there exist regolith breccias on the moon in which one of the characteristic features of authentic lunar regolith is, and always has been, absent. We propose that this absence of solar wind gases is not a secondary feature but that the constituents of Y-82192 were never exposed for any considerable length of time to the solar wind. Fragmental breccias such as those at North Ray, Apollo 16, fulfill this requirement.

It is perhaps of interest that the absence of large amounts of trapped gases is not the only feature which distinguishes Y-82192 from lunar meteorites Y-791197 and ALHA81005 and from genuine lunar regolith breccias. According to NAKAMURA *et al.* (1986) the lead isotope data of Y-82192 do not show the isotopic signature of lunar anorthosites, which is unique among all solar system material known to us, but they, "taken at face value, suggest that the lead is entirely meteoritic, with perhaps a small terrestrial component".

4. Conclusions

The Y-82192 meteorite is a lunar meteorite based on the same type of chemical evidence that was used to show that ALHA81005, and Y-791197 are lunar meteorites.

Despite an overall agreement in chemical composition there are some differences among the lunar meteorites. There is a trend of increasing concentrations of Cr, Sc, and V from ALHA81005 through Y-791197 to -82192. The contents of incompatible elements in Y-82192 are significantly lower than in the other lunar meteorites. This and the different REE pattern indicate the complete absence of KREEP, a front-side component that is rich in incompatible elements and that was at least partly distributed through impacts over the front-side of the Moon.

The Y-82192 lunar meteorite is also unique because of its lack of solar wind derived rare gases, that are so prominent in the other lunar meteorites. The sample analyzed by us was probably never exposed to the solar wind. This is consistent with petrographic observations.

Both Y-82192 and -82193 are shocked polymict fragmental breccias which contain only a very minor regolith component because glass spherules and other glass are extremely rare. We believe that the meteorites originate from a subregolith polymict fragmental megabreccia unit in analogy to the North Ray crater (Apollo 16) fragmental breccia which are also very low in solar wind implanted rare gases.

The types and frequency of lithic clasts in the two lunar meteorites indicate that their protolith is a typical highland megabreccia with abundant recrystallized anorthosites, granulitic lithologies and fine-grained feldspathic impact breccias.

From the clast population statistics and the mineralogical appearance of lithic and mineral clasts we conclude that Y-82192 and -82193 originate from the same meteorite. This is in agreement with the conclusions of TAKEDA *et al.* (1986). Chemical analyses of Y-82192 and -82193 reveal that both samples are possibly paired, and that the chemical compositions of their matrix are largely different from those of Y-791197 and ALHA81005 (FUKUOKA *et al.*, 1986).

Y-82192/193 has been shock lithified by an equilibrium peak pressure in the order of 10 GPa and was never shocked as a rock to pressures above 20 GPa. The shock lithification and the ejection from the moon may result from two different cratering events however one single event for both processes is equally possible.

All lunar meteorites (ALHA81005, Y-791197, Y-82192/193) represent lunar highlands material. However, we cannot rule out that two different impacts on the Moon's surface brought the meteorites to Earth. This is supported by the lack of KREEP in Y-82192/193 compared to ALHA81005 and Y-791197.

If the lunar meteorites were ejected by a single impact we believe that the samples were not close together or that the impact site was extremely heterogeneous as already suggested by WARREN and KALLEMEYN (1986).

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