Mem. Natl Inst. Polar Res., Spec. Issue, **46**, 43–55, 1987

MINERALOGY OF LUNAR METEORITES, YAMATO-82192 AND -82193 WITH REFERENCE TO BRECCIAS IN A BRECCIA

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Abstract: The mineralogy of pyroxene, olivine and plagioclase fragments, lithic clasts and glassy matrices of lunar meteorites, Yamato-82192 (Y-82192) and Yamato-82193 (Y-82193), has been studied by an electron microprobe and an analytical transmission electron microscope (TEM). The distribution of the chemical compositions of pyroxene grains in Y-82192 and -82193 bears a strong resemblance to one another and covers almost all known pyroxenes in nonmare pristine rocks. They are similar to those of a lunar regolith breccia 60019, but appear to be different from Y-791197 and ALHA81005 in that Y-82 lunar meteorites have significantly fewer pyroxenes with extremely high Fe content. The difference implies that Y-82192 and -82193 may contain a fewer Fe-rich mare basalt components. The presence of a breccia in a breccia in Y-82192 indicates complex impact histories in the region where this meteorite was derived. The texture of the matrix glass of Y-82192 in the TEM scale is different from that of ALHA81005.

1. Introduction

All lunar meteorites found to date, ALHA81005 (*e.g.* RYDER and OSTERTAG, 1983; WARREN *et al.*, 1983), Y-791197 (YANAI and KOJIMA, 1984), Y-82192 (YANAI *et al.*, 1984) and Y-82193 (YANAI and KOJIMA, 1985), are lunar highland, regolith breccias. Since breccias of this kind contain wide varieties of mineral signature of lunar crusts and mare basalts distributed around the impact sites, from where the meteorite was ejected, mineralogical studies of the lunar meteorites provide us with regional information on lunar highland rock types. The lunar meteorites will provide us with a wealth of information of the lunar crust comparable to those sampled by the U. S. Apollo and the Soviet Luna missions. Although pristine nonmare rocks (WARREN and WASSON, 1979) preserve faithfully the compositional variety of the original lunar crust, pristine fragments were very rare in our samples of Y-82192 and -82193.

Comparisons of four lunar meteorites are also important, because they inform us of local differences of rock types and differentiation trends within the lunar crust. The nature of the lunar crust and differentiation trends in different locations will give us important clue to solve the origin of the moon, especially to answer the question how the lunar crust solidified in space and time from a magma ocean. As the first step to approach such goal, we have to answer three questions: (1) are Y-82192 and -82193 the same meteorites?, (2) are Y-82 meteorites the same as other Antarctic lunar meteorites? and (3) are there any clues to the sites of their provenance on the moon? We investigated Yamato-82 lunar meteorites by employing mineralogical signatures of pyroxene, plagioclase, and matrix glass to gain better understanding of these problems.

2. Experimental Techniques

We studied two thin sections of Y-82192 and one thin section (,91–4) of Y-82193 supplied from the National Institute of Polar Research (NIPR) by the electronprobe microanalyzer (EPMA) and photomicroscope method and a small rock fragment of Y-82192 by the analytical transmission electron microscope (TEM) technique. Chemical analyses were made with a JEOL 733 Super Probe at the Ocean Research Institute of the University of Tokyo and at NIPR, by employing the same parameters and method as those used with JXA-5 by NAKAMURA and KUSHIRO (1970). Chemical zoning and phases unmixed by exsolution in pyroxenes were examined by measuring the chemical compositions at 10 to 50 microns intervals, with a JEOL probe.

The glass bulk compositions of the breccia matrices and matrices of glassy clasts of Y-82192,50–6 and -82193,91–4 were obtained by broad beam (40 microns) microprobe analyses (average of 5 to 10 spots) in order to plot them in the silica-olivine-plagioclase pseudo-ternary system.

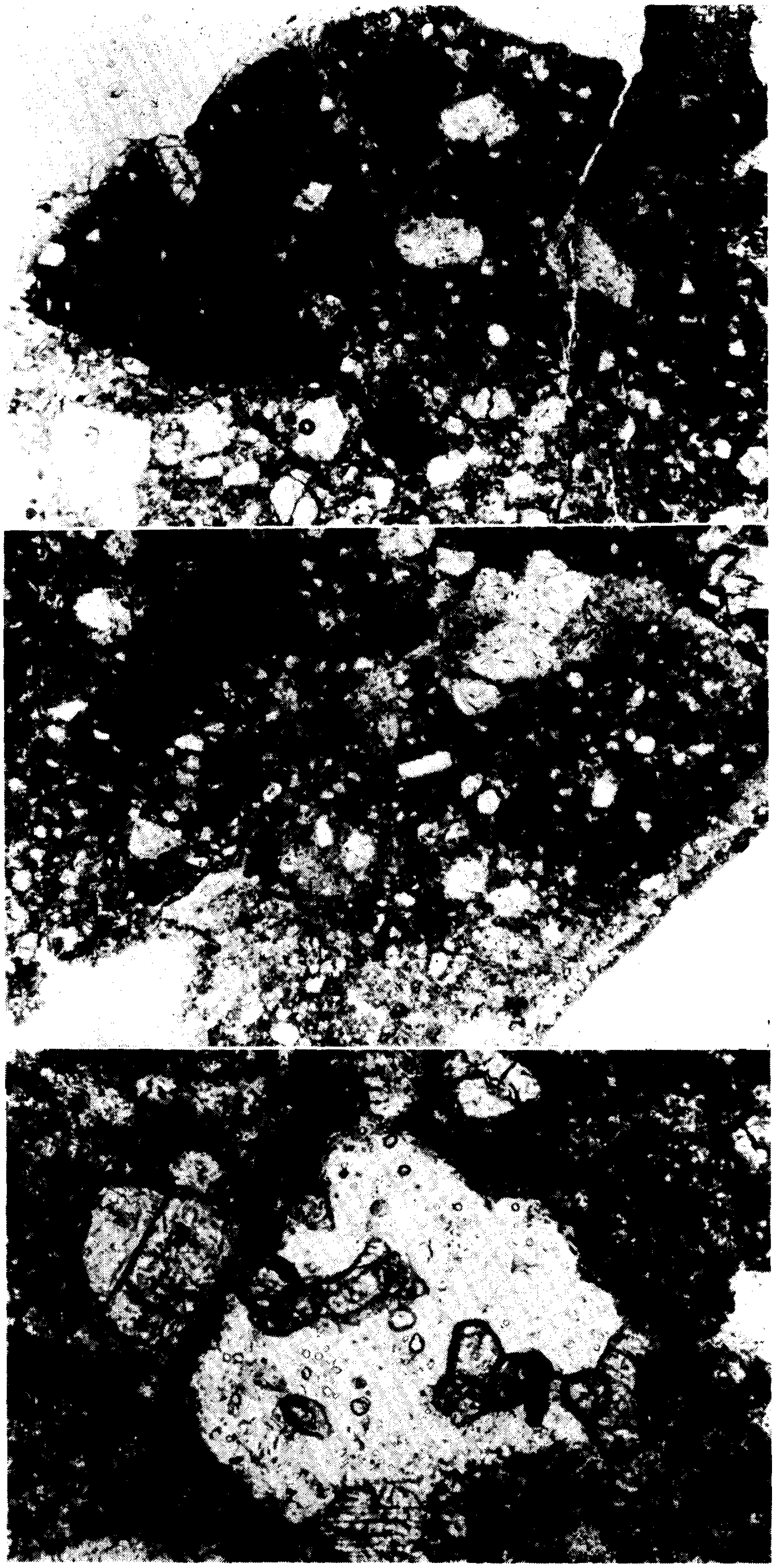
We also investigated a glassy matrix in a small chip of Y-82192 with a Hitachi H-600 analytical TEM, equipped with Kevex 7000Q system, which is capable of analyzing the chemical composition, texture and atomic arrangements of a region as small as 800 Å. The method is the same as was used for ALHA81005 (TAKEDA *et al.*, 1986a). The chip mounted in resin was sliced and polished to about a 10 microns thickness. The sample glued to a 3 mm molybdenum TEM grid for support was thinned in an GATAN ion-thinning machine until perforation occurred. Examination of microtextures of the sample was carried out by the analytical TEM.

3. Results

3.1. Y-82192

3.1.1. Physical description

Y-82192 is nearly a half of a whole stone weighing 36.67 g. Many cracks and a few deep cavities on the surface are observed. Sample Y-82192 is a regolith breccia partly coated with a thick devitrified impact-melt splash glass, although our thin section does not include this glass. Weathered surfaces are smooth, polished-looking. Scattered patches of orange weathering products are seen. A patch of greenish surface looks like fusion crust. One patch of glass might be former agglutinate produced when it was a regolith. The largest clast in the meteorite, approximately 15–20% of the whole stone, is a fine-grained impact melt, which contains a few scattered xenocrysts. Other large clasts include: 8×3 mm white clast with highly irregular shape, possibly shock-melted and probably weathered. Grayish-white clast 4.5×2 mm in size. White clast 4×2 mm in size. Another white, possibly weathered clast 3.5×2.5 mm in size (WARREN, personal communication, 1985).



a. Typical overall texture of Y-82192, 50–6, a vitric clast (upper left) is in the matrix. Width of photomicrograph is 3.3 mm.

b. BB breccia clast (lower right) in breccia matrix. Width is 3.3 mm.

c. Troctolitic (allivalitic) anorthosite clast in Y-82192 with minor pyroxenes. Width is 1.3 mm.

Fig. 1. Photomicrographs of clasts and matrices of Y-82192. Unpolarized light.

3.1.2. Lithic clasts

Y-82192 (the first PTS produced at NIPR) is a polymict breccia consisting of a matrix which is glass-rich and fine-grained mineral clasts. The glass probably is due to shock-produced intergranular melt (WARREN, personal communication, 1985). Lithic clasts include many subophitic impact melt clasts, light feldspathic and dark, more mafic impact melt clasts with microporphyritic textures, granulitic breccias, a poikilitic impact melt clast consisting of plagioclase and pyroxene. Other clasts include one glass bead, and one possibly agglutinate-type glass.

The most abundant lithology is impact melts. The amount of the impact melt clasts is larger than in Y-791197, and that of the granulitic breccias is apparently less than Y-791197. Granulite, the most abundant clast lithology in ALHA81005, is not that common in Y-82192. One small clast of anorthositic composition, with roughly 10% mafic silicate (probably olivine), appears pristine in texture. One "large" granulite clast is present. Glass is frequently recrystallized. Plagioclase in the matrix is slightly shocked (*i.e.* less than 20 GPa after OSTERTAG, personal communication, 1985). The matrix is glassy; most clasts are lighter than matrix. This feature resembles the "light matrix" of Apollo 16 breccias.

Y-82192,50–6 is a thin section of a regolith breccia, but the matrix is not crystalline as was reported previously (YANAI *et al.*, 1984). Y-82192,50–6 includes two large lithic clasts and fragments of crystalline to partly shock-melted plagioclases, and vitric clasts (Fig. 1a). The clasts vary in size, with the largest clast 3.6×1.7 mm in size. This clast is another regolith breccia (BB). This "breccia in a breccia" type clast is common in lunar samples, but such a good example (Fig. 1b) has not been reported in the lunar meteorites. The amount of matrix glass of BB is smaller than the host matrix and the bulk chemical composition of the matrix glass obtained by a broad beam analysis of EPMA is more feldspathic than the matrix of Y-82192 (Fig. 2). The distribution of the An mol% of plagioclase in the clast compares to that of the entire

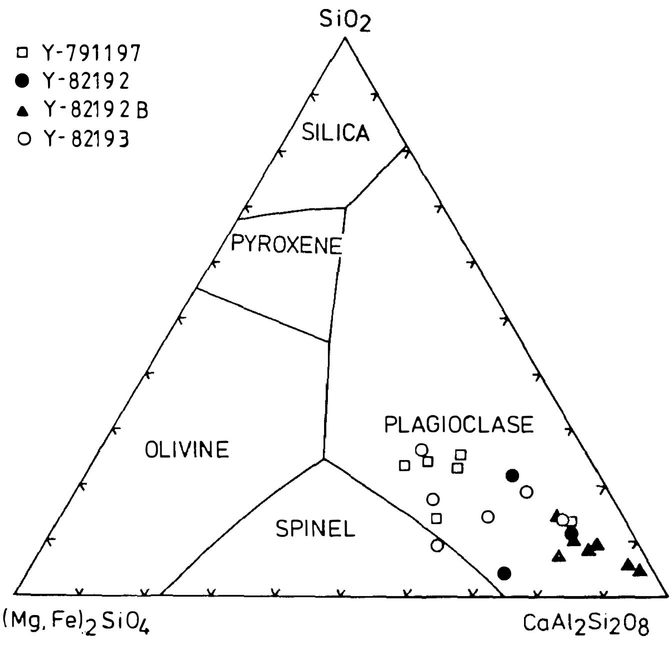


Fig. 2. Compositions of matrix glasses in Y-791197, Y-82192 and -82193 plotted in the silica-olivine-plagioclase pseudo-ternary system. Liquidus phase boundaries are quoted from WALKER *et al. (1972). Each symbol represents average values of five to ten individual analyses. Triangles: matrix glasses in the BB clast in Y-82192 (Y-82192B).*

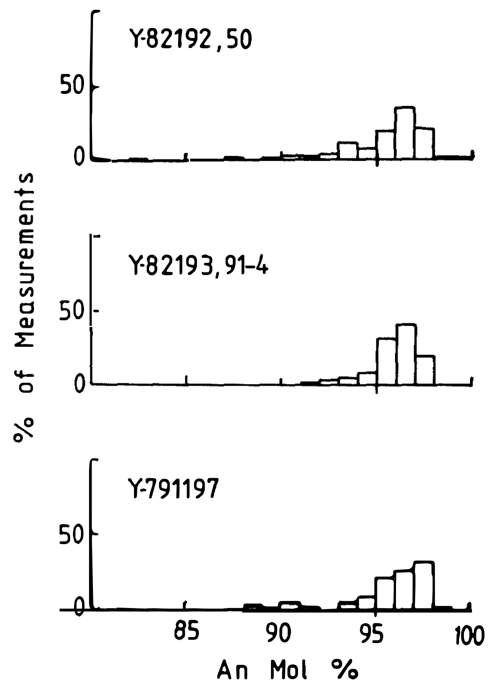


Fig. 3. Distribution of the An mol % of plagioclase in Y-82192 and -82193.

PTS shown in Fig. 3.

The second largest clast 1.6×1.4 mm in size is a glassy impact melt breccia with plagioclase fragments (Fig. 1a). The matrix glass is slightly devitrified. The outline of another such clast is not clear and its glass matrix merges into the surrounding glassy breccia matrix, and it looks like a glass-rich matrix. Other common clasts are cataclastic anorthosites. The only crystalline clast found within the thin section is a troctolitic (allivalitic in terrestrial terminology) anorthosite (TA) 0.85 mm in diameter (Fig. 1c) with a small amount of pyroxene with $Ca_{4.4}Mg_{59.0}Fe_{36.6}$ (Table 1, Fig. 4). The plot of mol% An (96.3) in plagioclase *vs.* mol% Mg/(Mg+Fe) (=mg) of the co-existing mafic minerals (mg of olivine=56.6 and mg of pyroxene=61.7) for this clast is within the ferroan anorthosite field (Fig. 5).

3.1.3. Pyroxene and feldspar

The compositions of small fragments of pyroxene in the Y-82192 matrix plotted in the pyroxene quadrilateral (Fig. 4) are distributed within the Mg-rich field of the lunar crustal rocks (RYDER and NORMAN, 1978a, b). This pattern is closer to that of 60019 than to Y-791197 (TAKEDA *et al.*, 1986a). Pyroxene compositions of the BB clast are within this field. The largest pyroxene fragment is an exsolved pigeonite crystal 0.55×0.35 mm in size and has coarse exsolution lamellae of augite 0.01 mm thick with about 0.05 mm intervals with common (001). The pyroxene composition is within the ferroan anorthosite field (open circle with the tie line in Fig. 4), but such pyroxene is found in lunar noritic rocks also (TAKEDA *et al.*, 1979).

The compositions of plagioclase fragments are similar to those of the other lunar meteorites (Fig. 3). The An mol% ranges from 87 to 99, but the most abundant range is between 95 and 98 with maximum population at 96.5 (Fig. 3).

Table 1. Chemical compositions of pyroxenes, olivines and plagioclases in lithic clasts in Y-82192, and in Y-82193.

Clasts	Y-82192 TA			Y-82193 BS		
Mineral	Oliv.	Pig.	Plag.	Pig.	Aug.	Plag.
SiO_2	35.2	54.2	43.9	51.6	50.1	43.7
Al_2O_3	0.04	1.03	35.0	0.76	1.71	35.0
TiO_2	0.05	0.38	0.04	0.84	0.84	0.03
Cr_2O_3	0.06	0.57	0.02	0.36	1.02	0.05
MgO	26.3	26.7	0.10	19.96	11.29	0.07
FeO	37.4	14.54	0.24	21.3	14.21	0.10
MnO	0.45	0.29	0.02	0.36	0.27	0.02
CaO	0.14	1.73	19.06	4.08	19.41	19.15
Na_2O	0.02	0.02	0.39	0.04	0.34	0.54
K_2O	0.01	0.01	0.04	0.00	0.02	0.03
Total	100.46	98.89	99.75	98.50	99.10	99.24
Cations	O=4	O=6	O=8	O=6	O=6	O=8
Si	0.994	1.965	2.050	1.953	1.932	2.048
Al	0.001	0.044	1.940	0.034	0.078	1.935
Ti	0.001	0.011	0.000	0.024	0.024	0.001
Cr	0.001	0.017	0.001	0.011	0.031	0.002
Mg	1.107	1.442	0.006	1.126	0.648	0.005
Fe	0.883	0.441	0.010	0.674	0.458	0.004
Mn	0.011	0.009	0.002	0.012	0.009	0.001
Ca	0.004	0.068	0.953	0.165	0.801	0.962
Na	0.001	0.002	0.034	0.003	0.010	0.049
K	0.000	0.000	0.000	0.000	0.001	0.002
Total	3.003	3.999	4.996	4.002	3.992	5.009
Ca/An/Fo*	55.6	3.5	96.3	8.41	42.0	95.0
Mg/Ab/Fa	44.4	73.9	3.48	57.3	34.0	4.84
Fe/Or		22.6	0.22	34.3	24.0	0.15

* Mol percent.

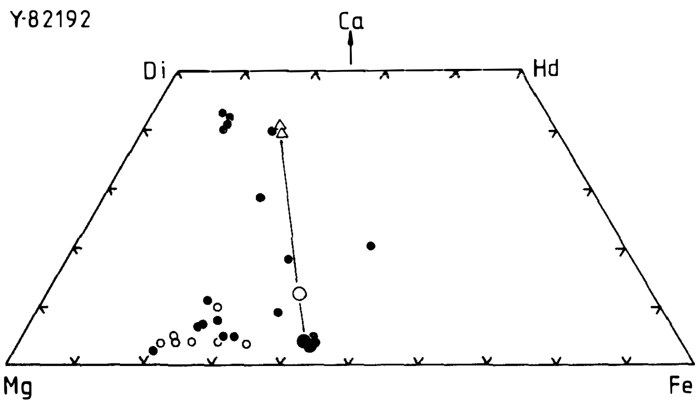


Fig. 4. Pyroxene quadrilateral of Y-82192. Solid circles are compositions of individual fragments of pyroxene in the matrix. Small open circles are from the BB clast. The tie line indicates exsolved pair. Large open circle: bulk composition of exsolved pigeonite. Large solid circles and open triangles: host and lamellae of the exsolved pigeonite, respectively.

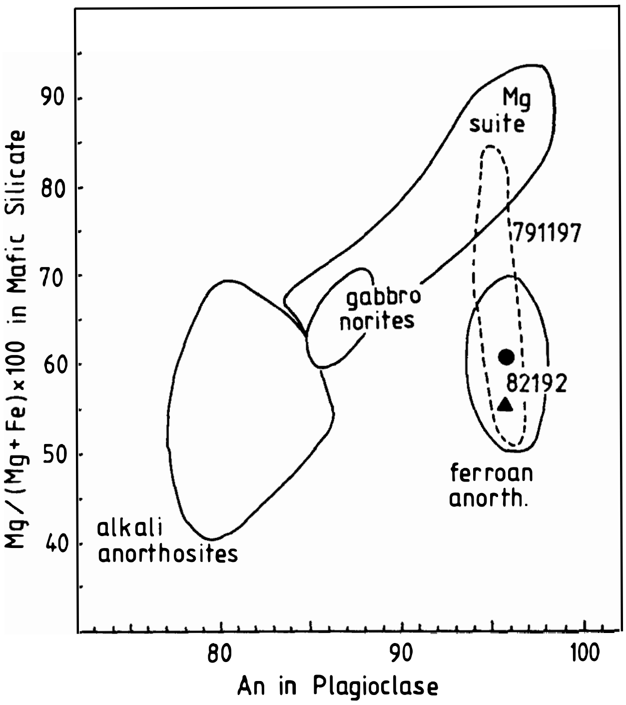


Fig. 5. The plot of mol% An in plagioclase vs. mg value of a crystalline clast in Y-82192. Field of the lunar differentiation trends is after RYDER *and* OSTERTAG *(1983).*

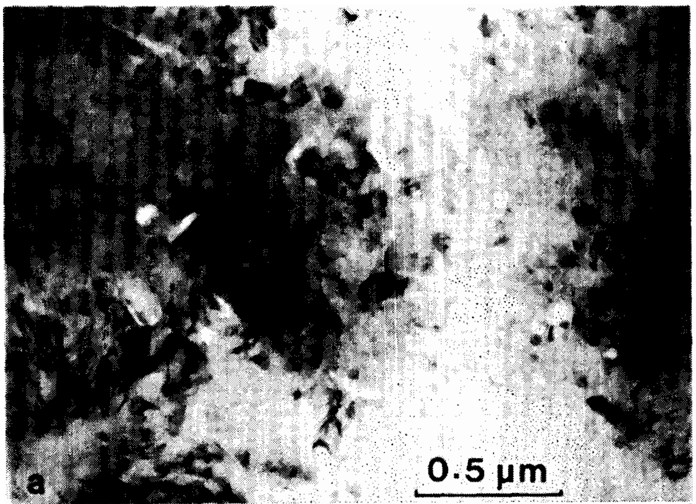


Fig. 6a. Transmission electron micrograph of very fine-grained matrix in Y-82192. Bright field.

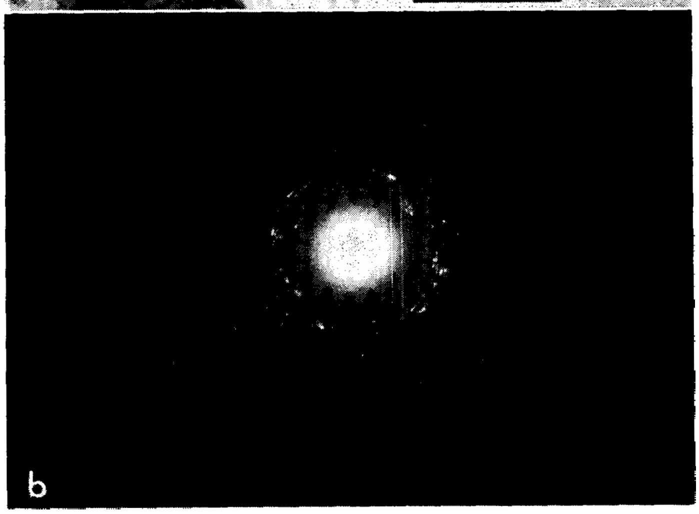
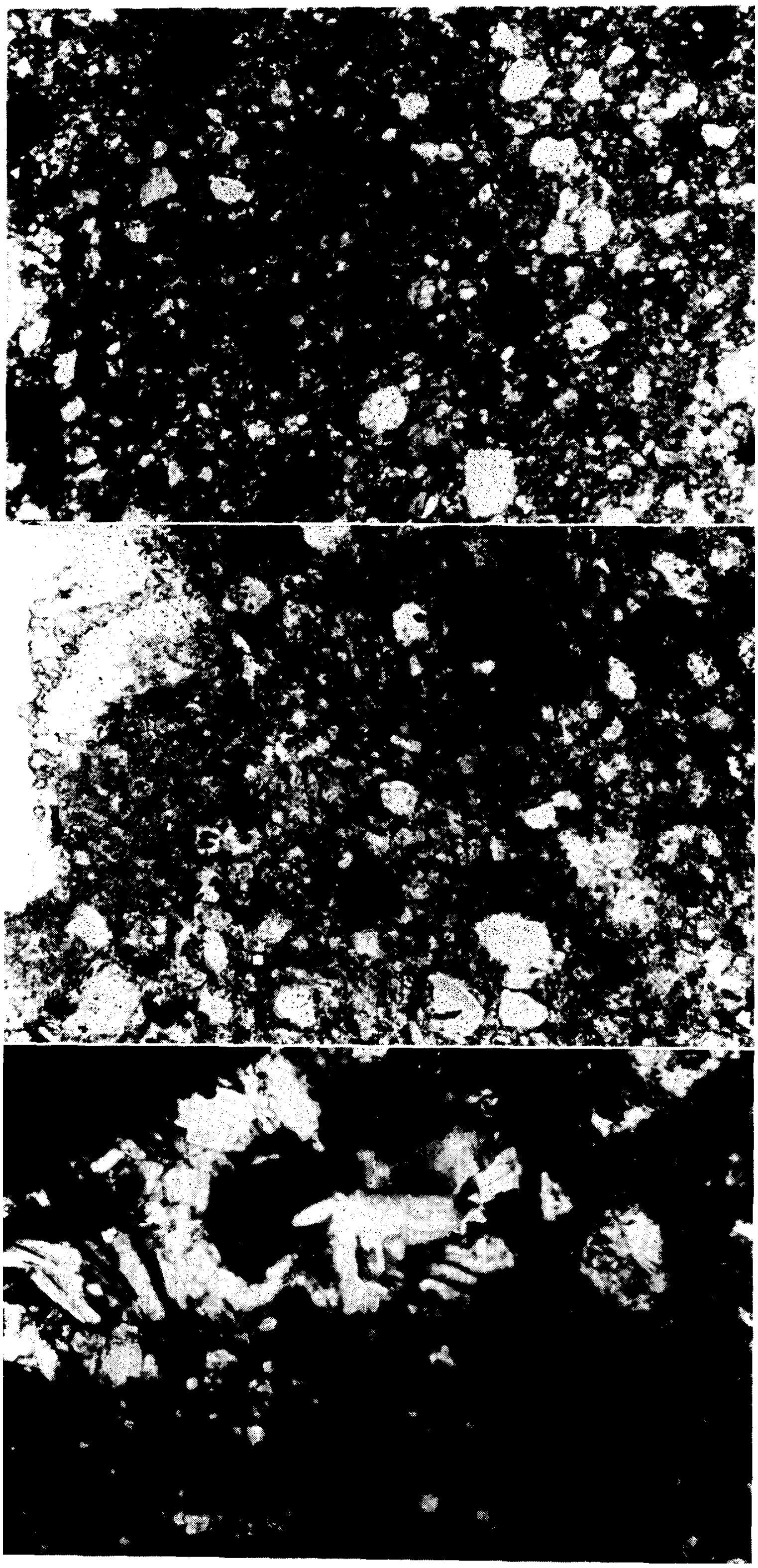


Fig. 6b. Electron diffraction pattern from the same region as Fig. 6a.



a. Typical overall texture of lunar glassy matrix regolith breccia, Y-82193, 91-4. Width is 3.3 mm.

b. Fine-grained recrystallized matrix breccia clast (left) in Y-82193. Width in 1.3 mm.

c. Crystalline impact melt clast (BS) in Y-82193. Cross-polarized light. Width is 1.3 mm.

Fig. 7. Photomicrographs of clasts and matrices of Y-82193.

3.1.4. Matrix

The matrix is fine-grained comminuted fragments of regolith components, and has smaller amounts of glass than Y-791197, and is similar to that of megaregolith breccias 60016 and 60019. The amount of glass differs from one place to another and glass-rich areas are similar to Y-791197.

TEM observation showed the fine-grained matrix glassy material consisting of micron-sized angular clastic fragments of silicate minerals and some very fine-grained (submicron-sized) interstitial silicate minerals (Fig. 6a). Both of the silicate minerals are primarily composed of plagioclase with small amounts of pyroxene and olivine. Very minor amounts of troilite and Ca-phosphate were also observed. Electron diffraction pattern from the very fine-grained interstitial silicate minerals shows that they are aggregations of many small crystals (Fig. 6b). They can be interpreted to be a result of solid-state recrystallization and to play a role of glue in the matrix material.

3.2. Y-82193

3.2.1. Description

Y-82193,90–4 is a thin section 10.5×5.3 mm in size of the matrix portion of the regolith breccia and has a uniform texture (Fig. 7a). The size of the clast fragments is smaller than the other lunar meteorites and ranges from 0.1 to 0.9 mm in diameter. Large lithic clasts are not present in this thin section, but are present in others. Cataclastic anorthosite clasts, very fine-grained recrystallized matrix breccias (Fig. 7b) and impact melt breccias are among the small clasts. The amount of glass appears to be larger because the thicker thin section reveals dark color, but may be smaller than Y-791197 and is distributed more evenly. The glass matrix compositions are rich in mafic components than those of Y-82192 (Fig. 2). This is consistent with the presence of abundant mafic silicate grains in the matrix.

3.2.2. Lithic clast

Only lithic clast found in our thin section of Y-82193 is a basaltic clast (BS) 0.94× 0.47 mm in size, which appears to be recrystallized noritic anorthosite or mare basalt (Fig. 7c). The pyroxene is zoned with compositional range from $Ca_6Mg_{59}Fe_{35}$ to $Ca_{42}Mg_{34}Fe_{24}$ with a gap in the middle (BS in Table 1, Fig. 8). The plagioclase composition in An % ranges from 90 to 96.

3.2.3. Pyroxene and feldspar

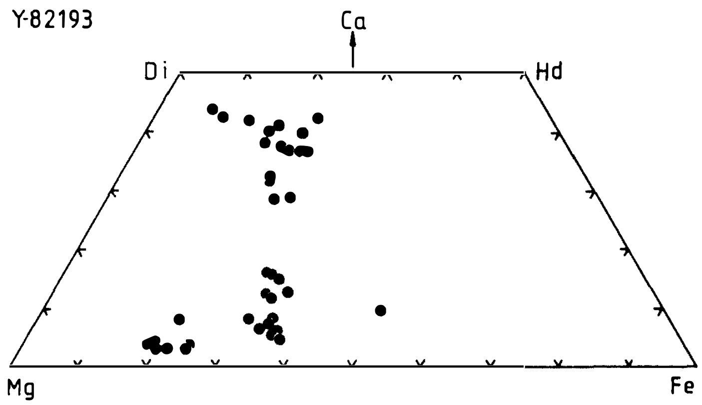


Fig. 8. Pyroxene quadrilateral of Y-82193. The symbols are the same as in Fig. 4.

The compositions of pyroxene fragments in the matrix are plotted in Fig. 8, which is similar to that of Y-82192 in that the Fe-rich portion is absent. The compositions of plagioclase fragments in the matrix are distributed also in a similar manner to Y-82192,50 with the mean composition of An 96.0 (Fig. 3). The An values in mol% range from 91 to 98, but are more heavily populated between 95 and 98.

3.3. *Minor cations of plagioclase in Y-82192 and -82193*

The chemical analysis of the shocked plagioclases and partly vitrified plagioclases in Y-82192 and -82193 by EPMA show considerable amounts of FeO and MgO. The number of Fe+Mg atoms per 8 oxygens is plotted against that of Si+Al atoms (the tetrahedral cations) and that of Ca+Na+K atoms (the octahedral cations) in Fig. 9 to demonstrate the mode of substitution in the structural formulae. The continuous increase of Fe+Mg was observed with decreasing Si+Al and Ca+Na+K, and the number of the tetrahedral cations decreases more severely against increasing Fe+Mg. This trend is different from those observed in the volcanic plagioclase and the volcanic glass of the feldspar composition. Therefore, the behaviors of the Fe+Mg atoms *vs.* the tetrahedral and octahedral cations in Fig. 9 may be characteristic in the shocked plagioclases.

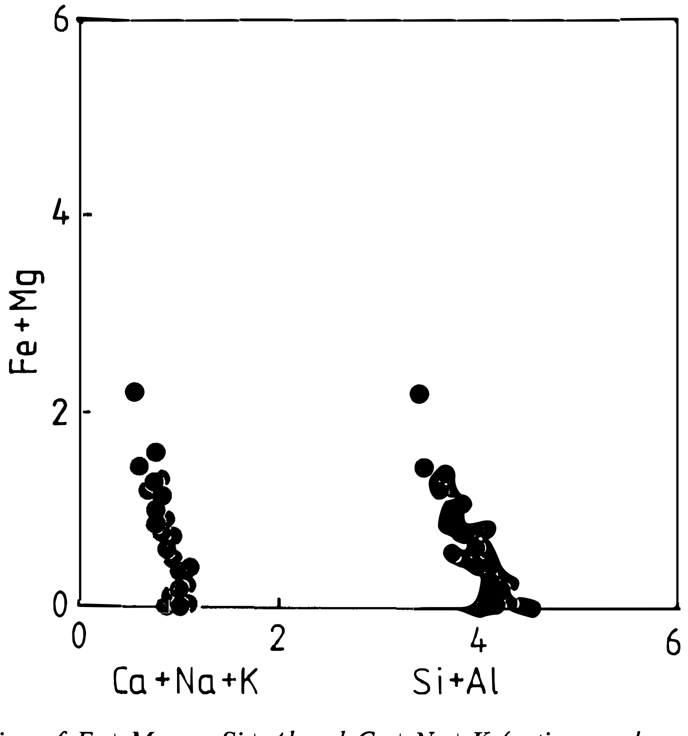


Fig. 9. Variation of Fe+Mg vs. Si+Al and Ca+Na+K (cation numbers per 8 oxygens) in the Y-82192 and -82193 plagioclases.

4. Discussion

4.1. *Comparison of Y-82192 and -82193*

Y-82192 was first reported as a crystalline matrix breccia (YANAI *et al.*, 1984), but the texture indicates that it is a regolith breccia with smaller amount of the matrix glass than that of Y-791197. The shock and recrystallization history appears to be similar to that of known regolith breccias of the Apollo collection (McKAY *et al.*, 1986), and Y-82192 has to be considered a regolith breccia, too. The finding of former agglutinate formed when it was regolith is significant because agglutinates are found only in regolith or regolith breccias. The fact that the matrix includes one perfectly round spherule of glass (partly recrystallized) is an excellent evidence that the sample is a regolith breccia (OSTERTAG, personal communication, 1985).

Comparison of Y-82192 and -82193 is difficult because the thin sections we studied are not representative of the entire samples. However, distribution of their pyroxenes in the matrices is very similar, suggesting that their source materials may be similar.

4.2. *Comparison of the Y-82 to other Antarctic lunar meteorites*

The textures and compositions of the matrix glasses, and clast population are different between Y-82192 and -791197. The absence of iron-rich variety of Y-82192 and -82193 pyroxenes is the most pronounced difference from other Antarctic lunar meteorites and partly may be due to a small number of sampling points, but suggests that they came from a region far from mare flows containing Fe-rich pyroxenes. The VLT basalt fragments present in ALHA81005 and Y-791197 contain very iron-rich pyroxenes (LINDSTROM *et al.*, 1985; WARREN *et al.*, 1983; TREIMAN and DRAKE, 1983). The Y-82 group may contain a mare basalt type with fewer Fe-rich pyroxenes such as low-Ti basalts. Another interpretation may be that Fe-rich metastable pyroxenes may have been melted by a shock event to produce iron-rich glassy matrix. However, Y-82192 contains less glassy matrix than Y-791197 does. The shock and recrystallization history of the Y-82 group appears to be similar to that of Y-791197 and ALHA81005.

The plagioclase compositions of all lunar regolith breccias are similar because the variation of the An content in highland rocks is within the limited range. This statement is another way of expressing that the ferroan anorthosite trend shows a small range in An content with respect to the larger variation in the mg number (Fig. 5). Because the Mg suite-trend of the highland rocks is absent and the ferroan anorthosite trend is present in the lunar meteorites, the An content should show smaller distribution. The An distribution of the plagioclase in the BB clast is as large as that of the entire PTS of the Y-82192, suggesting that the BB clast is also a polymict breccia.

4.3. *Comparison of Y-82 lunar meteorites with Apollo 16 regolith breccias*

The absence of iron-rich pyroxene varieties of Y-82192 and -82193 has been known for the Apollo 16 regolith breccias such as 60016 (TAKEDA *et al.*, 1979) and 60019 (TAKEDA*et al.*, 1985). A basalt fragment in 60019 includes very small proportion of iron-richpyroxenes (TAKEDA *et al.*, 1986b). These facts may indicate that either Y-82 lunar meteorites contain small amounts of the VLT component or mare components in Y-82 have lower abundance of high-Fe pyroxenes as is known for low-Ti basalt or Luna 16 basalt.

60016 and 60019 are lunar analogs of the lunar meteorites, with 60016 containing less matrix glass than 60019. Y-82192 is intermediate between 60016 and 60019. Since 60016 contains smaller amounts of solar wind gas components than normal regolith breccias, it was expected that Y-82192 would also contain smaller quantities of such gases. TAKAOKA (1986) confirmed this prediction. The small amount of solar wind gas components may indicate that Y-82192 was formed as a megaregolith.

The presence of glass in the matrix of Y-82192 requires minimum shock pressures larger than 10 GPa in a porous medium (OSTERTAG, personal communication, 1985). Large glassy particles with irregular shape, which is different from the glass bead particles, might have formed as the result of higher peak shock pressures from the same material that forms the bulk meteorite.

Considering the differences between 60016 and 60019, we cannot definitely state that Y-82192 is different from Y-82193, but Y-82 lunar meteorites may be different from other lunar meteorites if the absence of iron-rich pyroxene in Y-82 lunar meteorites is real. To answer this question, we have to study local variations of more regolith breccias recovered by the Apollo mission. There was found no unique clast which might locate the impact sites on the moon or to show new differentiation trends of the highlands. All clasts and pyroxene types are common ones among the lunar meteorites and lunar highland breccias.

4.4. Histories of the lunar regolith breccias

The presence of "breccia in a breccia" in Y-82192 suggests that there was a previous impact event before the formation of the present regolith breccia. The lithic clast in this BB breccia clast is mostly anorthositic and the matrix glass is more anorthositic than the matrix glasses of the host brecccia. This observation implies that the anorthosite-rich breccia was present before the impact event which produced this megaregolith of Y-82192. This finding is in agreement with our general understanding that complex impact and excavation histories were involved in forming lunar regolith breccias.

We thank Dr. K. YANAI and Mr. H. KOJIMA for the sample preparation and the equipments. A part of this study was supported by a Grant in Aid for Scientific Research from the Ministry of Education, Science and Culture. This work was also supported in part by the funds from Cooperative Program (No. 84134) provided by Ocean Research Institute, University of Tokyo. The preliminary description of the Y-82 lunar meteorites was kindly provided by Drs. P. H. WARREN and R. OSTERTAG. We thank Dr. P. H. WARREN for critical reading of the manuscript, Messrs. H. KOJIMA and O. TACHIKAWA for their technical assistances, and Miss M. ANDO for typing the manuscript.

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(Received September 10, 1986; Revised manuscript received January 8, 1987)