MINERALOGY OF ANTARCTIC LUNAR METEORITES AND DIFFERENTIATED PRODUCTS OF THE LUNAR CRUST

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Abstract: The mineralogy of clasts containing pyroxenes and glassy matrices of lunar meteorites, Yamato-791197 (Y-791197) and Allan Hills A81005 (ALHA81005) has been studied by an electron microprobe and an analytical transmission electron microscope (ATEM). A rare brown pyroxene-rich clast (HPF) consists of hedenbergite, Ca-poor iron-rich pyroxene, plagioclase, fayalite, silica and ilmenite. This exotic component may be a differentiated product of the lunar crust or an iron-rich portion of a basalt. The evolutionary trend of Y-791197 from spinel troctolite to anorthosite in the An content *vs.* Mg/(Mg+Fe) diagram is similar to that of ALHA81005 and is located between the Mg-rich suite of rocks and ferroan anorthosite. It is difficult to prove that this trend represents a single differentiation and that the HPF clast is on the extension of this trend, because the data appear to define a trend of extremely steep slope. The glass in the matrix of ALHA81005 is devitrified on the TEM scale.

1. Introduction

The first lunar meteorite, Yamato-791197, was recovered from the bare ice near the Yamato Mountains by the meteorite search party of the 20th Japanese Antarctic Research Expedition (JARE) in November 1979. Because of its resemblance to some carbonaceous chondrites, the sample was kept under frozen and clean conditions at the National Institute of Polar Research (NIPR) in Tokyo, Japan before it was characterized (YANAI and KOJIMA, 1984). Meanwhile, a small unusual meteorite collected from the Allan Hills, Antarctica (ALHA81005), by the U.S. party, was recognized as a 'lunar meteorite', a meteorite brought from the moon (*e.g.* WARREN *et al.*, 1983a). Now, all available data indicate that ALHA81005 is of lunar origin. Subsequently, Y-791197 and another sample recovered in 1982, Y-82192, have been described as the second and third lunar meteorites by YANAI and KOJIMA (1984) and by YANAI *et al.* (1984). All these samples are lunar highland, regolith breccias.

The closest precedents or analogs of the lunar meteorites in the Apollo and Luna samples have been proposed to be Apollo 16 and Luna 20 regolith (WARREN *et al.*, 1983a). However, in the previous studies on the lunar meteorites, efforts have been concentrated on proving their lunar origin. Their lunar analogs have not been too well characterized mineralogically for comparison with the lunar meteorites, although an Apollo 16 regolith breccia, 60016 was studied by TAKEDA *et al.* (1979). The distribution of pyroxene compositions of 60016 in the pyroxene quadrilateral is similar to those of ALHA81005 (RYDER and OSTERTAG, 1983) and Y-791197 (YANAI and KOJIMA, 1984), and they include almost all pyroxene types known in lunar highland rock types. Studies of lunar meteorites, therefore, provide us with information of various samples of the lunar highland rock types from a wider area of the moon where each meteorite was derived.

No other extensive study has been undertaken to find and compare lunar meteorites with their closest analogs among lunar samples collected by the Apollo missions. To locate the impact sites of the lunar meteorites, to find whether all lunar meteorites were derived from the same meteorite impact on the lunar surface, or if they are pieces of a single meteorite fall over the Antarctic continents, we have to study more regolith breccias recovered by the Apollo missions. This kind of lunar rock has been very poorly characterized up to date, because we have been more interested in pristine, crystalline rocks which formed the primary lunar crust in the earliest history of the solar system. Because there was more glass in the matrix of ALHA81005 and Y-791197 than 60016, another sample which more closely resembles the lunar meteorites (Dr. D. MCKAY, personal communication, 1984), 60019, is being investigated by our group (MIYAMOTO *et al.*, unpublished data, 1985).

Comparisons of the three lunar meteorites are also extremely important, because they inform us about portions of the Moon's crust never sampled by either the U.S. Apollo or the Soviet Luna missions. Those missions provided samples from only a tiny region near the center of the near side, comprising about 4.7% of the entire lunar surface (WARREN *et al.*, 1983b). Thus, the probability that a meteorite such as Y-791197 originated from outside of the Apollo-Luna sampling area is about 95%; and we can be virtually certain that careful study will provide important new clues to the Moon's composition, origin and evolution. If all three lunar meteorites were different, the scientific value of each sample would be comparable to the value of one lunar mission.

We planned to investigate pyroxene-rich clasts as part of the consortium study of Y-791197, but clasts are not as common in Y-971197 as in ALHA81005. Our study includes a rare clast (HPF) with hedenbergite, plagioclase, fayalite and silica. We tried to see whether the glass matrix was produced by the impact which produced this breccia or by a later impact which propelled this sample from the Moon to the Earth. In order to gain a better understanding of lunar regolith breccias, comparisons have been made with two large lunar regolith breccias, 60016 and 60019 (TAKEDA *et al.*, 1985).

2. Samples and Experimental Techniques

Y-791197,120-1 is a relatively thick polished thin section (PTS) prepared for studying a brown pyroxene-rich clast (HPF) found during sample preparation for the consortium study. The PTS is 7×4 mm in size and the plane of the PTS cut is nearly perpendicular to a disk-like clast, which is 2.2×0.4 mm in size on the PTS. In this PTS, there is another large grayish clast rich in plagioclase (PK1), 2.7×1.5 mm in size. The remainder of the PTS consists of fine-grained fragments of plagioclase, glass and minor mafic minerals, set in dark brown glassy matrix. Some plagioclase fragments are shock-darkened, or partly melted showing a suevite-like texture.

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 Ca, Mg and Fe concentrations at 10 to 50 micron intervals, with a JEOL probe.

The glass bulk compositions of the breccia matrices and matrices of glassy clasts of Y-791197, 60016 and ALHA81005 were obtained by broad beam (40 microns) microprobe analyses (average of 5 to 10 spots) and are plotted in the Al_2O_3 *vs.* CaO (wt %) diagram (not given in this paper) and in the silica-olivine-plagioclase pseudo-ternary system.

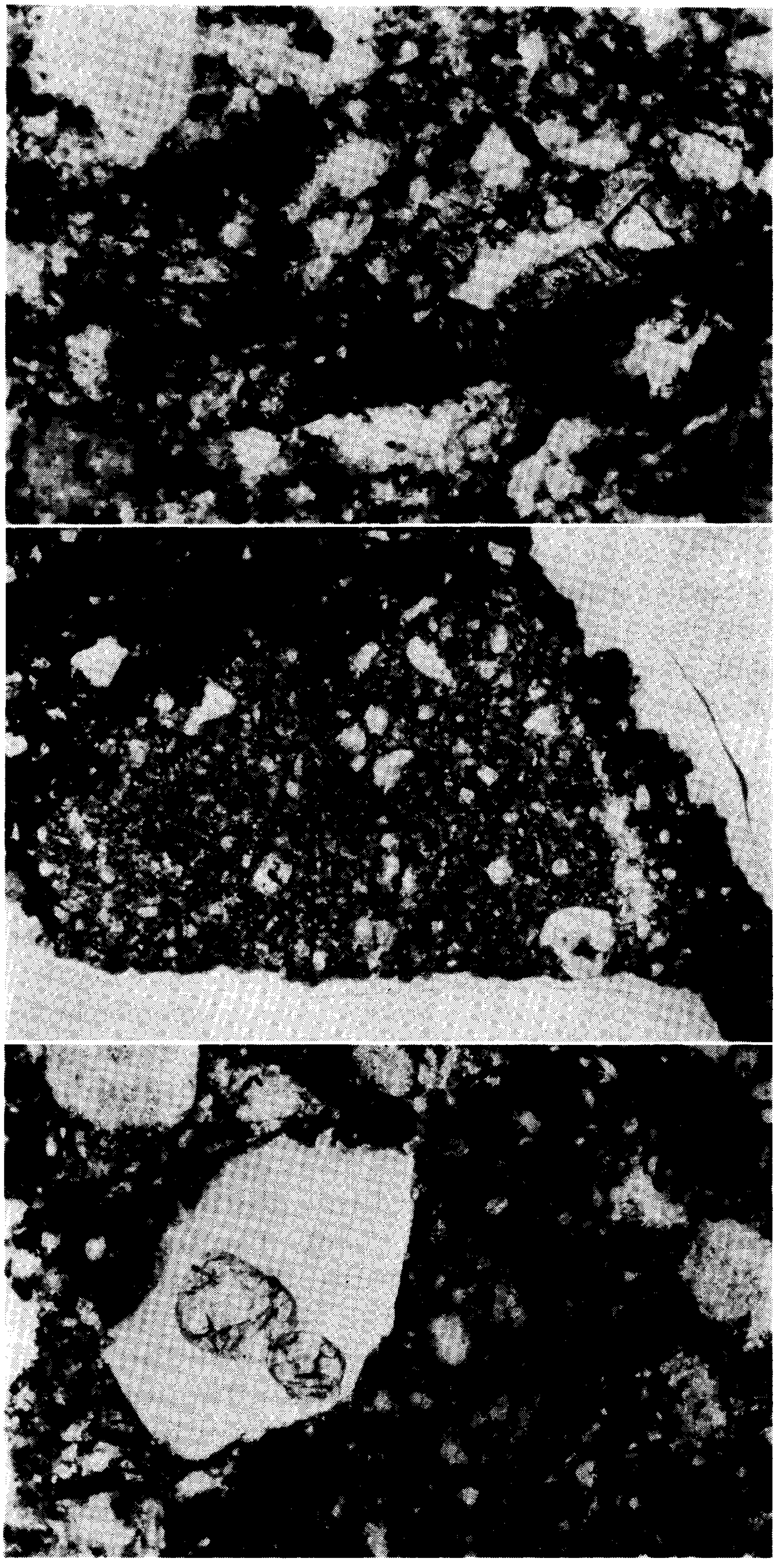
We also investigated a glassy matrix in a small chip of ALHA81005 with a Hitachi H-600 analytical transmission electron microscope (ATEM), equipped with Kevex 7000Q system, which is capable of analyzing the chemical composition, texture and atomic arrangements of a region as small as 800 Å. The chip was mounted in thick resin onto a glass slide, then sliced and polished to about a 10 microns thickness. The sample was removed from the glass slide and glued to a 3 mm molybdenum TEM grid for support and was thinned in an Edwards ion-thinning machine until perforation occurred. Examination of microtextures of the sample was carried out by ATEM.

3. Results

The HPF clast (Fig. 1a) consists of dark yellowish brown to reddish brown iron-rich pyroxene, small amounts of plagioclase, fayalite, and dark mesostasis-like materials including fayalite, minor silica mineral and ilmenite. Their chemical compositions are shown in Table 1. The pyroxene is zoned from Ca-rich pigeonite (or pyroxyferroite?) to hedenbergite (Fig. 2). The zoning trend is mainly Fe-Ca substitution in the high-Fe pyroxene, and the major portion is almost pure hedenbergite. The plagioclase is Na-rich, and the range of the composition is from An 90 to 91 with the mean value 90.5. Because the clast is very thin, it is difficult to visualize the whole texture, but it is relatively coarse-grained with the grain size of pyroxenes about 0.2 mm in diameter.

The PK1 clast has a texture with a few subround plagioclase crystals up to 0.2 mm in diameter set in a fine grayish poikilitic-like matrix (Fig. 1b). Fine-grained (up to 30 microns) olivine and pyroxene are rarely found in the matrix. The plagioclase compositions are calcic and the An content ranges from 95 to 97. The Fa content of olivine ranges from 36 to 49. Other small lithic clasts found in Y-791197 are: noritic and troctolitic anorthosites and shocked anorthosites. The chemical compositions of minerals in representative clasts are given in Table 2. The pyroxene compositions are plotted in the pyroxene quadrilateral (Fig. 3).

One clast (SA) consists of rounded euhedral pleonaste spinel enclosed in anorthite (Fig. 1c). This clast could be a fragment of spinel cataclasite, which has lead many workers to suggest the possibility of a lower crustal or upper mantle origin, *e.g.*, HERZBERG (1978). However, SA does not contain olivine, high alumina orthopyroxene or cordierite. It could be a spinel-anorthite rock. Another spinel-anorthite clast has been found in 60019 (TAKEDA, unpublished data, 1985).

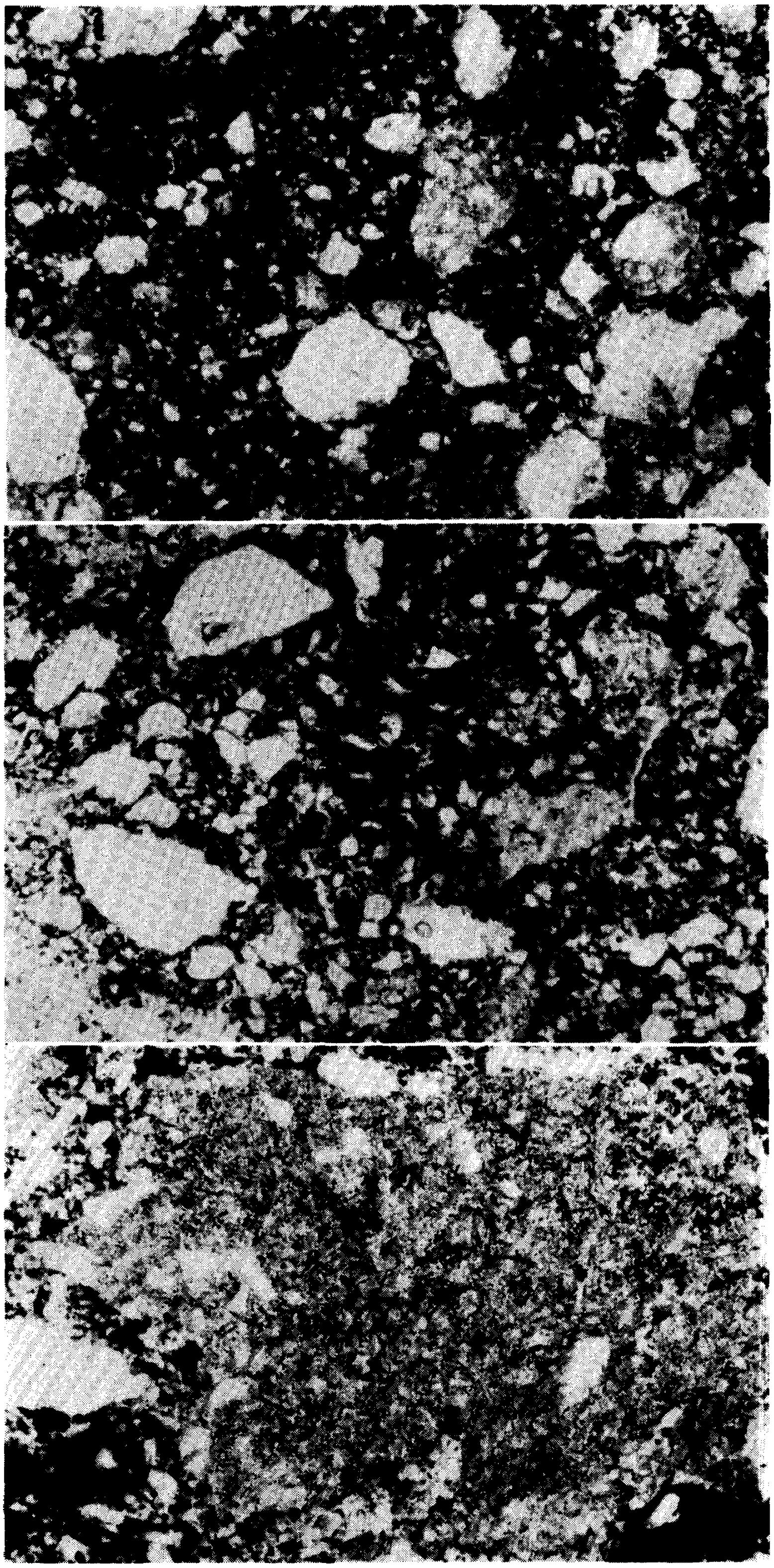


a. HPF clast of Y-791197 in matrix. Width is 1.3 mm. Horizontal thin disc-like clast in the middle of the photo.

b. PK1 clast in Y-791197. Width is 1.3 mm.

c. SA clast in Y-791197 with two spinel crystals in plagioclase. Width is 1.3 mm. PTS by courtesy of Y. IKEDA.

Fig. 1. Photomicrographs of clasts and matrices of Y-791197 and 60019. Unpolarized light.



d. Typical over all texture of Y-791197. Width is 3.3 mm.

e. Typical over all texture of lunar glassy matrix regolith breccia, 60019. Width is 3.3 mm.

f. Poikilitic crystalline matrix clast in 60019. Width is 1.3 mm.

Fig. 1. Photomicrographs of clasts and matrices of Y-791197 and 60019. Unpolarized light.

Table 1. Chemical compositions (wt %) of minerals in the HPF clast of Y-791197.

Mineral	Hedenbergite	Pigeonite	Plagioclase	Fayalite	Silica	Glass*
SiO_2	47.1	46.8	48.3	29.9	99.9	45.3
Al_2O_3	1.43	0.62	30.3	0.03	0.44	25.2
TiO_2	1.53	0.48	0.03	0.10	0.37	0.22
Cr_2O_3		0.16		0.03		0.14
FeO	30.8	39.5	2.11	67.2	0.59	6.46
MnO	0.36	0.53	0.04	0.77		0.09
MgO	0.93	4.49	0.05	0.95	0.01	5.86
CaO	18.12	6.11	17.72	0.73	0.14	15.15
Na_2O	0.02	0.01	1.04	0.03	0.05	0.32
K_2O	0.00		0.04		0.00	0.03
Total	100.24	98.64	99.67	99.66	101.48	98.91
Cations	O=6		O=8	O=4	O=2	O=8
Si	1.937	1.972	2.245	1.004	0.990	2.176
Al	0.069	0.031	1.660	0.001	0.005	1.428
Ti	0.047	0.015	0.001	0.003	0.003	0.008
Cr		0.006		0.001		0.005
Mg	0.057	0.282	0.003	0.048	0.000	0.420
Fe	1.059	1.392	0.082	1.887	0.005	0.260
Mn	0.013	0.019	0.002	0.022		0.004
Ca	0.798	0.276	0.883	0.026	0.002	0.780
Na	0.002	0.001	0.094	0.002	0.001	0.030
K			0.002			0.002
Total	3.982	3.994	4.972	2.994	1.006	5.114
Ca/Ab/Fo	41.7	14.1	9.6	2.5		
Mg/An/Fa	3.0	14.5	90.2	97.5		
Fe/Or	55.3	71.4	0.2			

* Glass could be a intruded matrix into the HPF clast.

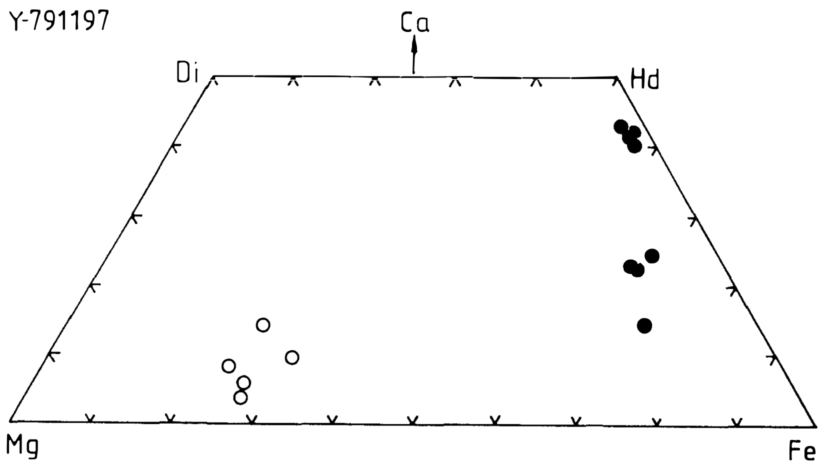


Fig. 2. Pyroxene quadrilateral of Y-791197. Solid circle: hedenbergite-plagioclase-fayalite (HPF) clast. Open circle: noritic and troctolitic clasts.

Table 2. Chemical compositions of minerals in representative clasts in Y-791197.

Mineral	Spinel	Olivine	Pyroxene		Plagioclase		
Clast	SA	TA1	TA1	NA	SA	TA1	NA
SiO_2	0.01	37.1	52.8	54.1	43.0	43.3	43.4
Al_2O_3	65.5	0.03	0.70	1.44	36.1	35.3	36.4
TiO_2	0.13	0.05	0.69	0.76	0.06	0.05	0.00
Cr_2O_3	4.26	0.05	0.38	0.52	0.00	0.00	0.34
MgO	23.1	34.6	24.8	29.0	0.21	0.08	0.00
FeO	6.91	27.7	17.66	11.15	0.03	0.22	0.04
MnO	0.07	0.25	0.29	0.28	0.00	0.01	0.01
CaO	0.00	0.13	2.11	1.73	19.08	19.58	19.51
Na_2O	0.02	0.00	0.04	0.04	0.33	0.47	0.46
K_2O	0.01	0.00	0.00	0.03	0.02	0.04	0.02
Total	100.02	99.92	99.47	99.01	98.77	99.07	99.89
Cations	O=24	O=4	O=6		O=8		
Si	0.001	0.992	1.947	1.942	2.011	2.026	2.010
Al	11.482	0.001	0.031	0.061	1.991	1.950	1.991
Ti	0.014	0.001	0.019	0.021	0.002	0.002	0.000
Cr	0.501	0.001	0.011	0.015	0.000	0.000	0.001
Mg	5.123	1.381	1.366	1.551	0.015	0.006	0.000
Fe	0.860	0.619	0.545	0.335	0.001	0.009	0.002
Mn	0.009	0.006	0.009	0.009	0.000	0.000	0.000
Ca	0.000	0.004	0.084	0.067	0.957	0.982	0.969
Na	0.007	0.000	0.003	0.002	0.029	0.043	0.041
K	0.001	0.000	0.000	0.001	0.001	0.002	0.001
Total	17.998	3.005	4.015	4.004	5.007	5.020	5.015
Fo/Ca/Ab		69.1	4.2	3.4	3.0	4.2	4.1
Fa/Mg/An		30.9	68.5	79.4	96.9	95.6	95.8
Fe/Or			27.3	17.1	0.1	0.2	0.1

Among the polished thin sections of lunar regolith breccia 60019, reexamined by TAKEDA *et al.* (1985), large areas of 60019, 14, 75, 80 and 91 (Fig. 1e, f) are similar in texture to lunar meteorites ALHA81005 and Y-791197. They are characterized by brown glass matrix, varieties of lithic and mineral fragments, and glassy components of lunar highland regoliths. A lunar light matrix breccia, 60016 has smaller amounts of such glass matrices than does 60019, but the clast materials are similar.

60016,97 consists of the fine-grained comminuted regolith constituents such as rock, mineral and glass fragments, glass spherules with mineral fragments, and glassy agglutinates. These are agglomerated to a coherent breccia by sintering of hot glass or by shock lithification. Some portions of the glass matrix and breccia clasts with plagioclase and mafic mineral fragments show more similar appearance to the lunar meteorites than is the over-all PTS. Large lithic clasts with mafic minerals are less abundant than in ALHA81005. The abundance of large clasts in ALHA81005 is also higher than that in Y-791197.

The glass compositions of the breccia matrices in Y-791197, ALHA81005 and 60016 plotted in the silica-olivine-plagioclase pseudo-ternary system (Fig. 4) show that all groups are distributed in a similar region. Since glasses were produced by heating

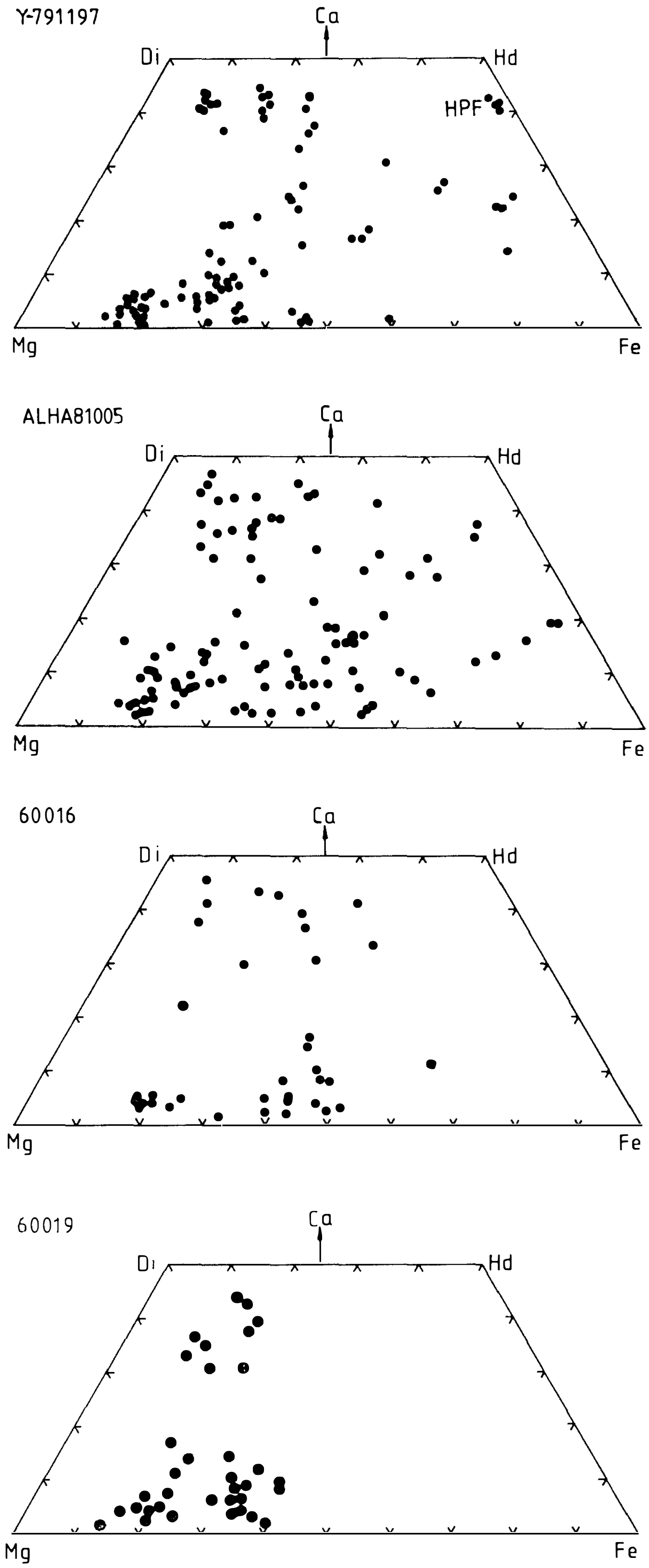


Fig. 3. Pyroxene quadrilaterals of pyroxene grains in the matrices of Y-791197, ALHA81005, 60016 and 60019. A part of the data is from YANAI *and* KOJIMA *(1984),* RYDER *and* OSTERTAG *(1983), and* TAKEDA *et al. (1979, 1985).*

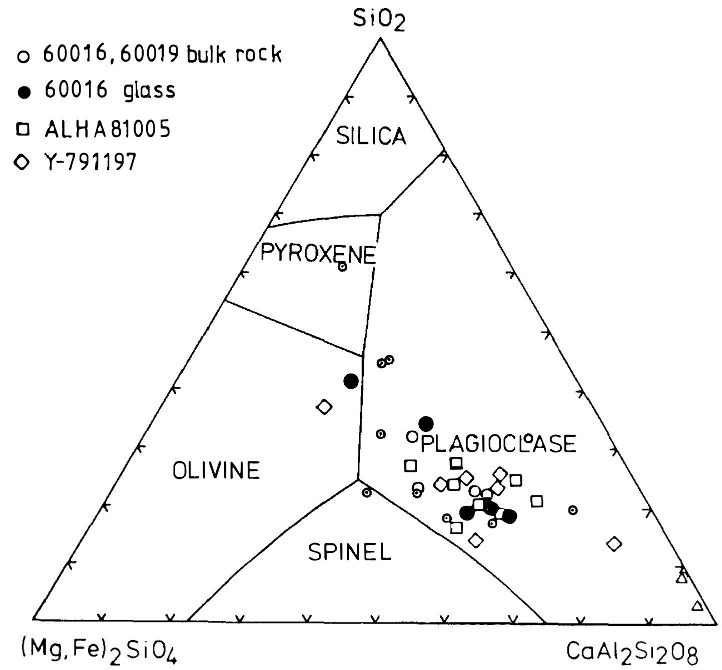


Fig. 4. Glass compositions of Y-791197, ALHA81005 and 60016 plotted in olivine-silica-anorthite pseudo-ternary diagram. Small circle with a dot represents an individual analysis of 60016. Bulk rock compositions (open circle) of 60016 and 60019 are also given. Triangles are anorthositic clasts in 60016.

of fine-grained fragmental materials of lunar highland rocks, the similarity in glass compositions suggests that they were derived from similar source materials.

The chemical compositions of all pyroxene grains in 60016 analyzed by electron microprobe are plotted in a pyroxene quadrilateral (Fig. 3) and are compared with those of pyroxenes in pristine nonmare rocks compiled by RYDER and NORMAN (1978a, b). Pyroxenes of rapidly cooled KREEP basalts and of the most Mg-rich troctolites are not present. They are also compared with those in ALHA81005 (RYDER and OSTERTAG, 1983) and Y-791197 (YANAI and KOJIMA, 1984). The compositions are distributed over a wide range in the quadrilateral, covering almost all known pyroxenes in nonmare pristine rocks. The olivine compositions of 60016 studied previously (TAKEDA *et al.*, 1979) also show that they represent those of the above rock type.

The distributions of the plagioclase compositions of large fragments in the matrix of the entire PTS, compared with fragments in the glassy clasts of 60016, are also similar but some plagioclases in glassy clasts show higher potassium contents. The number of plagioclase grains occurring in ALHA81005 is too small to compare them with Y-791197, 60016 and 60019, but the variation within 60016 is larger than within ALHA-81005.

The ATEM study of suevite-like glass veins in ALHA81005 revealed that glass-like materials are devitrified to fine recrystallized plagioclase (a few μm in diameter). The plagioclase shows a twin texture. No true glass was found in portions of ALHA-81005 we examined. Olivine and pyroxene crystals showing a poikilitic anorthosite-like texture are distributed as islands. The size of each olivine crystal is about a few microns. Some pyroxenes show a fine exsolution texture, indicating spinodal decompostition in the Ca-rich areas. The tweed-like texture turns into the exsolution texture by coarsening of specific lamellae. This indicates rapid cooling within a surface regolith breccia. Some of the features observed in ALHA81005 such as devitrification of shock-produced plagioclase glass are similar to microstructure of breccias 15418 observed by CHRISTIE *et al.* (1973).

4. Discussion

The compositional variations of pyroxenes in lunar meteorites and their analogs plotted in pyroxene quadrilaterals (Fig. 3) give us most valuable information on the components of lunar highland regoliths, because their compositions and inversion and exsolution textures are often unique signatures of certain rock types (TAKEDA *et al.*, 1979). The compositional trends of the two lunar meteorites studied thus far and those of 60016 and 60019 are within a region of pyroxenes present in pristine nonmare rocks of the lunar crust (RYDER and NORMAN, 1978a, b). Very Mg-rich pyroxenes are not common, but the amount of sample we studied is too small to discuss their absence.

The most noteworthy finding in terms of composition of pyroxenes (Fig. 3) is that ALHA81005 and Y-791197 bear a strong resemblance to one another and both contain extremely Mg-poor pyroxenes, whereas 60016 and 60019 both appear to have significantly fewer pyroxenes with extremely low Mg content. This difference suggests that the former two came from a region close to mare basalt flows, whereas 60016 and 60019 came from a region far from all mare flows (WARREN, personal communication, 1985). Another interpretation may be that low Mg pyroxenes in the forbidden zone of the pyroxene quadrilateral may have been melted by a shock event to produce iron-rich glassy matrix.

The relation between the anorthite content of plagioclase and the Mg number= Mg/(Mg+Fe) in coexisting mafic minerals in Y-791197 are plotted in Fig. 5. This trend is intermediate between that of the Mg-rich suites of the lunar highland crust and that of ferroan anorthosite. Similar trends were seen in ALHA81005 (TREIMAN and DRAKE, 1983). The SA clast is on the most Mg-rich portion of the trend. Magnesian lithologies such as the SA clast are probably not even relatives of the ferroan anorthosites, much less the ultra-ferroan HPF clast. Therefore, the HPF clast may not be on the extension of these trends, but it is possible that the most Ab-rich end of the ferroan anorthosite trend could approach that of the HPF clast. If this is the case, the HPF clast may be the last differentiated product of the anorthositic crust. The augite-rich clast found in ALHA81005 by WARREN and KALLEMEYN (1985) is located on the line from the center of the ferroan anorthosite field to the HPF clast. Only one other such hedenbergite was reported, for a granite clast 14321, 993 by WARREN *et al.* (1983b).

Some mare basalts contain small amounts of hedenbergite. The coarse-grained texture of the HPF clast may support the proposed origin of the late differentiated product. However, the presence of chemical zoning in the low-Ca pyroxene in the forbidden zone of the pyroxene quadrilateral and of the mesostasis-rich portion suggest

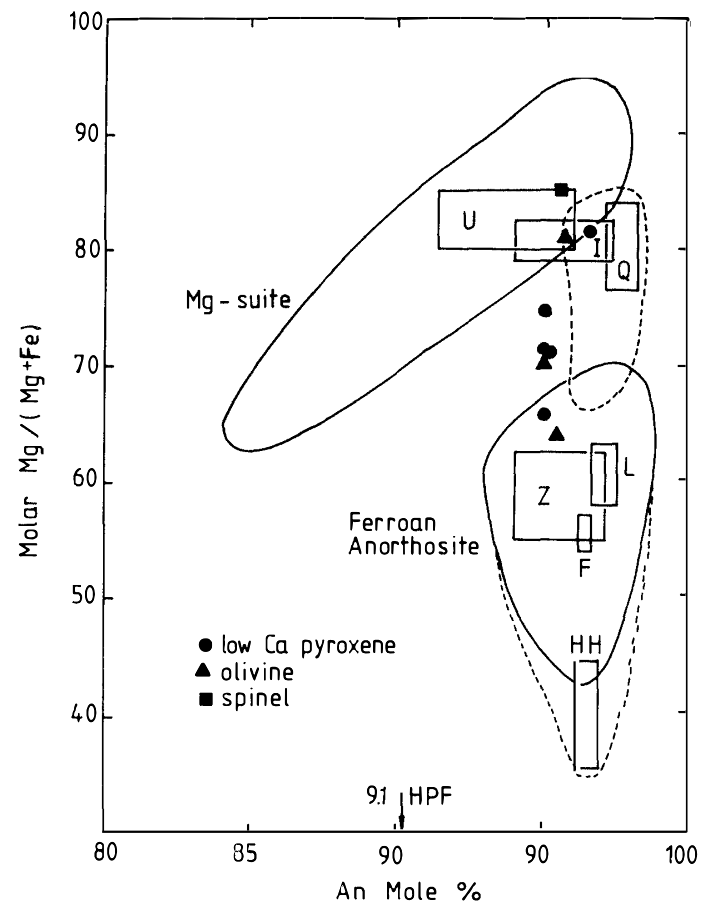


Fig. 5. The relation between the anorthite (An) content of plagioclase and the Mg number= Mg/(Mg+Fe) in coexisting mafic minerals in lunar meteorite, Y-791197 (solid circle for low-Ca pyroxene, solid triangle for olivine, and solid square for spinel in SA) plotted in a lunar highland diagram of TREIMAN *and* DRAKE *(1983). Regions enclosed by lines or dotted lines are after them.*

that the clast may be a differentiated product of a lunar highland or mare volcanism. The glass composition has a much higher Mg ratio than any of the minerals, and the glass may not belong to the HPF lithology. LINDSTROM *et al.* (1985) reported of finding a number of low-Ti mare basalt clasts in Y-791197. It may be likely that this HPF clast is the differentiated portion of a mare basalt, but the Mg-rich portion of the zoned pyroxene is not represented in the matrix elsewhere, except for clast II-4 of YANAI and KOJIMA (1984). The HPF clast might be an unrepresentative piece of a low-Ti mare basalt.

The pyroxene in the II-4 clast is chemically zoned from Mg-rich Ca-poor core to Fe- and Ca-rich rim. The HPF trend is on the extension of the clast II-4 trend. The coarse variolitic texture of II-4 suggests that it grew relatively rapidly from a melt. The chemical trend is similar to that of KREEP basalt, but the REE contents of Y-791197 are very low (TAKAHASHI *et al.*, 1986). The HPF clast could be more differentiated portion of the KREEP-less KREEP trends, since KREEP component is low in the lunar meteorites. One reason why a basalt fragment with low Mg has moderate An may be explained by low alkali abundance of the region where this meteorite was derived.

In the first description of Y-791197, YANAI and KOJIMA (1984) mentioned a resemblance of the bulk chemistry of Y-791197 and those of Apollo 15 breccia 15418 and Luna 16 breccia 21D13, but their mineralogy and petrology was not mentioned to support the similarity. Because Y-791197 is a lunar regolith breccia, any kind of lunar regolith breccia has some resemblance, by definition. Such characteristic feature should not be used to locate an impact site of the lunar meteorites.

Some regolith breccias are not rich in trapped solar wind gases. 60016 is an example of such a breccia and is proposed to represent a mega regolith produced by a large impact in the early history of the moon (BOGARD *et al.*, 1985). Many regolith breccias from the Apollo 16 site (*e.g.* 60019) are characterized by the presence of clasts of poikilitic crystalline matrix breccia. Clast PK1 in Y-791197 has a texture similar to this poikilitic rock, but the matrix is finer grained and the poikilitic texture has not been well developed. This kind of clast looks gray in hand specimen and may be a clast type common in Y-791197.

The bulk glass compositions of the matrix and clast types suggest that ALHA81005 and Y-791197 are similar. Their bulk rock compositions are also similar to those of 60016 and 60019 (Fig. 4). As represented in their bulk chemistry, the only difference is that the lunar meteorites contain lithic clasts more rich in mafic minerals than 60016 and 60019. 60019 contains more glassy matrix than 60016. Considering the difference between 60016 and 60019, we cannot deny a hypothesis that two lunar meteorites were derived by the same impact event.

The ATEM study of a glass in ALHA81005 suggests that the glass was not produced by the meteorite impact that excavated its mass into orbit towards the Earth. The glass had been devitrified on the lunar surface before excavation, and new glass was not produced by the last impact. Further study of the Y-791197 and 60019 glasses is required to be certain of this.

In summary, the agreement of the pyroxene chemical trends and the differentiation trends in the An *vs.* Mg number diagram of ALHA81005 and Y-791197 indicates that the two lunar meteorites were derived from the same impact event. However, the same features also differ between Apollo 16 regolith breccias 60016 and 60019. Before we draw a definite conclusion on this subject, we have to know the nature of local differences of regolith breccias at the Apollo 16 site and heterogeneity of such breccias within a sample.

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