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Mineralogical Studies of Lunar Mare Meteorites EET87521 and Y793274

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Mineralogical comparisons of lunar meteorites EET87521 and Y793274, possibly derived from a mare region of the Moon, have been performed to find quickly cooled basaltic components and slowly cooled plutonic materials. Basaltic components in both EET87521 and Y793274 contain strongly zoned Fe-Ca-rich pyroxenes like those found in the VLT basalts. A mesostasis portion found in a basaltic clast of EET87521 consists of ilmenite, minor Cr-Ti spinel mantled by fayalite Fo_{10}, and fine-grained mixtures of hedenbergite and fayalite, in contact with a silica mineral. Magnesium-rich materials are rare in EET87521 but are abundant in Y793274. Y793274 contains the most Mg-rich clast (PI) with orthopyroxene ($Ca_2Mg_{80}Fe_{18}$) and ilmenite, a gabbroic clast with finely exsolved pigeonite, olivine, and plagioclase, and pyroxene clasts intermediate between those in the basaltic and the Mg-rich clast types. The lath-shaped ilmenite in PI is the most Mg-rich ilmenite found in the lunar samples (MgO 8 wt%). A pyroxene fragment in EET87521 observed by a transmission electron microscope (TEM) shows exsolution lamellae of augite about 300 nm wide, which is consistent with the mare basalt origin. The transitional nature between clast types suggests that these Mg-rich clasts are early crystallized components in a thick lava unit, and that components with hedenbergite, fayalite, Na-rich plagioclase, and silica may be the most differentiated product. The TEM study of the glassy matrix of Y793274 shows that true glass produced by the last shock event has been preserved.

INTRODUCTION

All known lunar meteorites before 1989 were identified as regolith breccias of highland origin (e.g., *Ryder and Ostertag,* 1983; *Warren and Kallemeyn,* 1991). The compositions of pyroxene fragments in these lunar meteorites and regolith breccias from the highlands are distributed over a wide range in pyroxene quadrilaterals, covering almost all known pyroxenes in nonmare pristine rocks (*Takeda et al.,* 1979, 1988). These magnesian nonmare pyroxenes include inverted pigeonites with characteristic exsolution and inversion textures known in plutonic rocks and slowly cooled orthopyroxenes in norites and granulites. Therefore, the textures exhibited by such slowly cooled, plutonic magnesian pyroxenes can be used as criteria in the first step toward identifying nonmare pyroxenes (*Takeda et al.,* 1979).

Since 1989, four lunar meteorites (EET87521, Y793274, Y793169, and Asuka-31) have been proposed as derived from a mare region of the Moon (*Delaney,* 1989; *Warren and Kallemeyn,* 1989; *Yanai,* 1991; *Takeda et al.,* 1990a). We studied EET87521 and Y793274 by mineralogical techniques, including electron probe microanalysis, and compared them with Apollo and Luna mare basalts (*Papike et al.,* 1976). *Delaney* (1989) and *Warren and Kallemeyn* (1989, 1991) have proposed that some highland components are mixed in these two lunar meteorites. Clast types and pyroxene mineralogy have been used to identify the relationship to known lunar mare basalts and highland rocks. We also searched for slowly cooled plutonic pyroxenes common in lunar meteorites from the highlands on the basis of the above criteria, but we were unable to find such mineral components in them. However, we admit that there are other types of highland components in these meteorites.

Microtextures of glassy matrices of lunar meteorites have been used to identify paired specimens and to deduce ejection histories of the lunar meteorites (*Takeda et al.,* 1990b). However, no direct evidence of shock textures recorded at the time of ejection of lunar meteorites, which eventually brought them to the Earth, was found (*Takeda et al.,* 1990b). We investigated glassy matrices of Y793274 and EET87521 and a pyroxene fragment in EET87521 by transmission electron microscope (TEM) to deduce its cooling, brecciation, lithification, and shock histories.

SAMPLES AND EXPERIMENTAL TECHNIQUES

We investigated a polished thin section (PTS) EET87521,55 supplied by the Antarctic Meteorite Working Group (AMWG) and PTS Y793274,91-2 supplied by the National Institute of Polar Research (NIPR). Both samples were studied as part of two consortium studies (*Lindstrom et al.,* 1991; *Takeda et al.,* 1990a). Mineral chemistries and textures of the PTSs were examined by an electron probe microanalyzer (EPMA) and scanning electron microscope (SEM), JEOL 840A with X-ray chemical map analysis (CMA) utilities of Kevex Super 8000. Glassy matrices in small chips of Y793274,98 from NIPR (*Takeda et al.,* 1990a) and of EET87521,45 from AMWG were studied by analytical TEM. Chemical analyses were made with a JEOL EPMA (8600 Super Probe) at the Geological Institute, University of Tokyo, employing the same standards, parameters, and method used by *Nakamura and Kushiro* (1970). Exsolution in pyroxenes was examined by measuring the chemical compositions at 2-10-μm intervals.

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We also measured Mg-Fe and CaO chemical zoning profiles of olivines and pyroxenes in basaltic clasts and fayalite fragments in EET87521 and Y793274 with a JEOL EPMA (JCXA-733) at Ocean Research Institute, University of Tokyo. We measured zone profiles selected by backscattered electron images (BEI). The acceleration voltage was 15 kV and beam current was 30 nA on a Faraday cage. The measuring conditions are the same as reported previously (*Takeda et al.,* 1990b).

We also investigated glassy matrix and pyroxene in small chips of Y793274 and EET87521,45 with JEOL 100CX and 2000FX TEM and a Hitachi H-600 analytical TEM equipped with a Kevex Super 8000 system, which is capable of analyzing the chemical composition, texture, and atomic arrangements of regions as small as 800 Å. The method is the same as that for ALHA81005 (*Takeda et al.,* 1986). The chip mounted in resin was polished to a thickness of about 10 μm. The sample was glued to a 3-mm molybdenum TEM grid for support and then thinned in a GATAN ion milling machine until perforation occurred. Examination of microtextures of the samples was carried out by the analytical TEM.

RESULTS

EET87521

The EET87521,55 PTS consists of shocked basaltic clasts and their comminuted fragments, mineral fragments of pyroxene, olivine, and plagioclase set in matrices of glassy materials. Some parts of the matrices are darker than the others (*Lindstrom et al.,* 1991). At one corner of the PTS there is a large basaltic clast (BS1) measuring 5.8 × 5.5 mm (Fig. 1a). Much smaller basaltic clasts (e.g., BS2) are also found in the matrix. Many parts of BS1 are shock-disturbed and its subangular fragments are set in a brown swirly glass. The rounded laths of plagioclase are also shocked, and parts of them are maskelynitized or partly melted. The pyroxene crystals are up to 1.4 × 1.0 mm and show extensive chemical zoning.

Chemical compositions of pyroxenes in the BS1 clast and those of a mesostasis portion (Table 1) are shown in the pyroxene quadrilateral (Fig. 2). The zoning trend distributes more at the Fe-rich side of the pyroxene quadrilateral toward Hd (hedenbergite). The pyroxene-plagioclase ratio (volume) is about 2:1. The An-content of plagioclase crystals (Table 2) ranges from 94 to 82 (Fig. 3). Pyroxenes in other basaltic clasts (e.g., BS2) and fragments in the matrix show a similar chemical trend to BS1 (Fig. 2).

There is a mesostasis region in one corner of the most Fe-Ca-rich end of a pyroxene crystal in the BS1 near a plagioclase crystal (Fig. 1b). It consists of ilmenite and minor Cr-Ti spinel (Table 3) and the portion near the pyroxene is mantled by fayalite. Between the ilmenite and pyroxene portions there is a dark fine-grained mesostasis portion with fine-grained hedenbergite with blebs of fayalite. A large silica mineral is attached to this mesostasis.

Of three plagioclase-rich clasts about 1 mm in diameter, one (FB2) contains Fe-rich pyroxenes close to Hd, but another (FB1) contains one of the Mg-rich pyroxenes with the least chemical zoning with Mg# [= 100× Mg/(Mg+Fe)] = 54-46 (Fig. 2). Because their plagioclase crystals show lath shapes (Fig. 1c) and chemical zoning (Fig. 3) due to rapid growth, these clasts are not plutonic rocks (*Papike et al.,* 1976).

One small (<1 mm) lithic clast (GB2) with a medium-grained texture consists of hedenbergite and Na-rich plagioclase (An_{73}) (Tables 1 and 2; Fig. 3). This clast is one of the most differentiated rocks in EET87521. Such a lithic clast with hedenbergite, fayalite, plagioclase, and silica has been reported in Y791197 as an HFP clast (*Takeda et al.,* 1986). Its major- and trace-element chemistry is reported by *Warren and Kallemeyn* (1991).

The chemical compositions of pyroxenes in small lithic clasts and pyroxene fragments larger than about 100 μm are shown in Fig. 2. The pyroxenes have been examined for possible nonmare components such as magnesian-inverted pigeonites and granulitic orthopyroxenes, which have been reported in the lunar highland meteorites (*Takeda et al.,* 1990b). In spite of an extensive search for the plutonic components, all Mg-rich pyroxenes have been found to be part of a quickly cooled pyroxene (mostly pigeonite) with chemical variations due to rapid crystal growth and fine exsolution textures. They are different from plutonic pyroxenes reported for the nonmare rocks (*Takeda et al.,* 1979).

The An contents of plagioclase fragments in EET87521 are compared with those of Y793274 and a lunar meteorite from the highlands (MAC88105) in Fig. 4. There is no peak for the highland plagioclase as in MAC88105 and the compositions extend to the more Ab-rich side. The main plagioclase fragments are from the BS1-like basalts, but the contribution to the Na-rich plagioclase is from hedenbergite-bearing rocks such as GB2.

Forsterite contents of olivine in EET87521 are compared with those of Y793274 and lunar highland meteorite MAC88105 in Fig. 5. Small amounts of Mg-rich olivines found in EET87521 are similar to those in Y793274 and there is no strong reason to believe that they are from plutonic crustal rocks because they are similar to olivines in a gabbroic clast (BG2) in Y793274. Iron-rich olivine fragments are similar to those of the VLT basalts and that found in the mesostasis of BS1 in EET87521. One of the characteristics of EET87521 is that there are many fayalite fragments (Fo_4 to Fo_{10}) with high Ca contents, which are zoned from Ca# [= 100× Ca/(Ca+Mg+Fe)] = 0.9-1.5 mol%. This fayalite may be associated with a clast with hedenbergite and Na-rich plagioclase as in GB2 (Tables 1 and 2; Fig. 3) or with the mesostasis portion of the basalts.

Y793274

Y793274,91-2 PTS is a fragmental breccia richer in angular mafic minerals than plagioclase (Fig. 1d). Clast-laden glassy breccia and a few glass spherules and glassy fragments are also present. In one region, fragments of pyroxene, olivine, and plagioclase are set in a white (transparent) maskelynitized plagioclase matrix, rimmed in part by swirly glass (see Fig. 2b of *Takeda et al.,* 1991). This granulite-like clast (GR1) was thought to be a highland lithic clast (*Yanai and Kojima,* 1987a,b) because of its plagioclase-rich mineralogy. However,

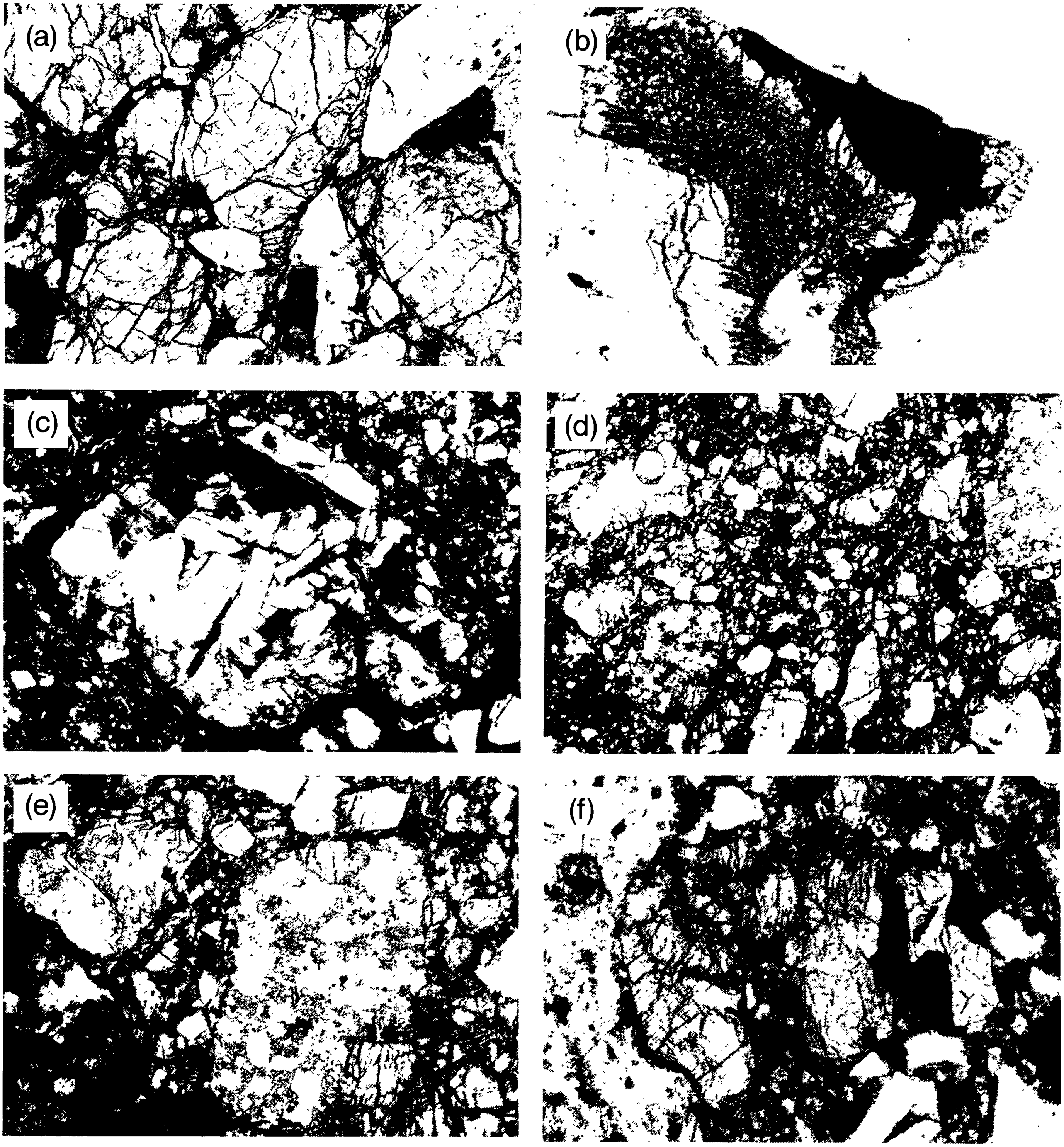

Fig. 1. Photomicrographs of clasts and matrices in EET87521 and Y793274; unpolarized light except for **(c)**. **(a)** Basaltic clast, BS1 in EET87521. Width = 3.3 mm. **(b)** A mesostasis portion of BS1 in EET87521. Dark portion in the middle. A silica mineral is at lower right. Width = 0.65 mm. **(c)** Feldspathic basaltic clast (FB3). Cross-polarized light. Width = 1.3 mm. **(d)** A general view of Y793274. GB2 clast at upper left and a fine-grained basaltic clast at upper right. Width = 3.3 mm. **(e)** Clast-laden feldspathic breccia with recrystallized matrix in Y793274. Width = 1.3 mm. **(f)** Opx-ilmenite clast (PI) on the right and an exsolved pyroxene facing GR1 clast on the left in Y793274. Width = 0.65 mm.

TABLE 1. Chemical composition (wt%) of pyroxenes in EET87521 and Y793274.

	EET87521					Y793274			
	Pyx (BS1 core)	Pyx (BS1 rim)	Pyx (BS1 meso)	Hd (BS1 meso)	Hd (GB2)	Opx (PI)	Pyx (GB2 host)	Pyx (Frag Mg-rich)	Pyx (Frag Fe-rich)
SiO_2	49.4	46.6	47.4	47.6	47.2	54.2	52.3	51.1	48.2
Al_2O_3	0.91	0.91	0.75	1.16	0.93	0.95	1.10	1.26	0.83
TiO_2	0.49	0.94	0.93	1.14	1.09	0.70	0.23	0.45	0.98
FeO	29.0	37.1	35.9	26.9	28.2	11.65	18.17	18.98	33.3
MnO	0.47	0.44	0.46	0.39	0.36	0.23	0.34	0.39	0.37
MgO	9.38	4.84	4.44	4.45	2.87	29.9	23.0	12.71	6.44
CaO	9.96	9.06	9.87	17.63	18.20	1.19	2.27	14.00	9.91
K_2O	0.00	0.00	0.01		0.00	0.02	0.07	0.01	0.04
Na_2O	0.05	0.01	0.07	0.09	0.11	0.01	0.08	0.04	0.02
Cr_2O_3	0.31	0.15	0.04	0.01	0.12	0.42	0.49	0.45	0.17
V_2O_3	0.03	0.03		0.04	0.00	0.05	0.00	0.06	0.09
Total	100.0	100.1	99.9	99.4	99.1	99.3	98.1	99.5	100.4
Ca*	21.8	20.3	22.4	39.3	41.2	2.3	4.7	30.1	22.1
Mg	28.6	15.1	14.0	13.8	9.0	80.2	66.0	38.0	20.0
Fe	49.6	64.7	63.6	46.9	49.8	17.5	29.3	31.9	58.0

*Atomic %.

Pyx: pyroxene, Hd: hedenbergite, Opx: orthopyroxenes, meso: mesostasis, frag: fragment.
Names in parentheses are clast names explained in text.

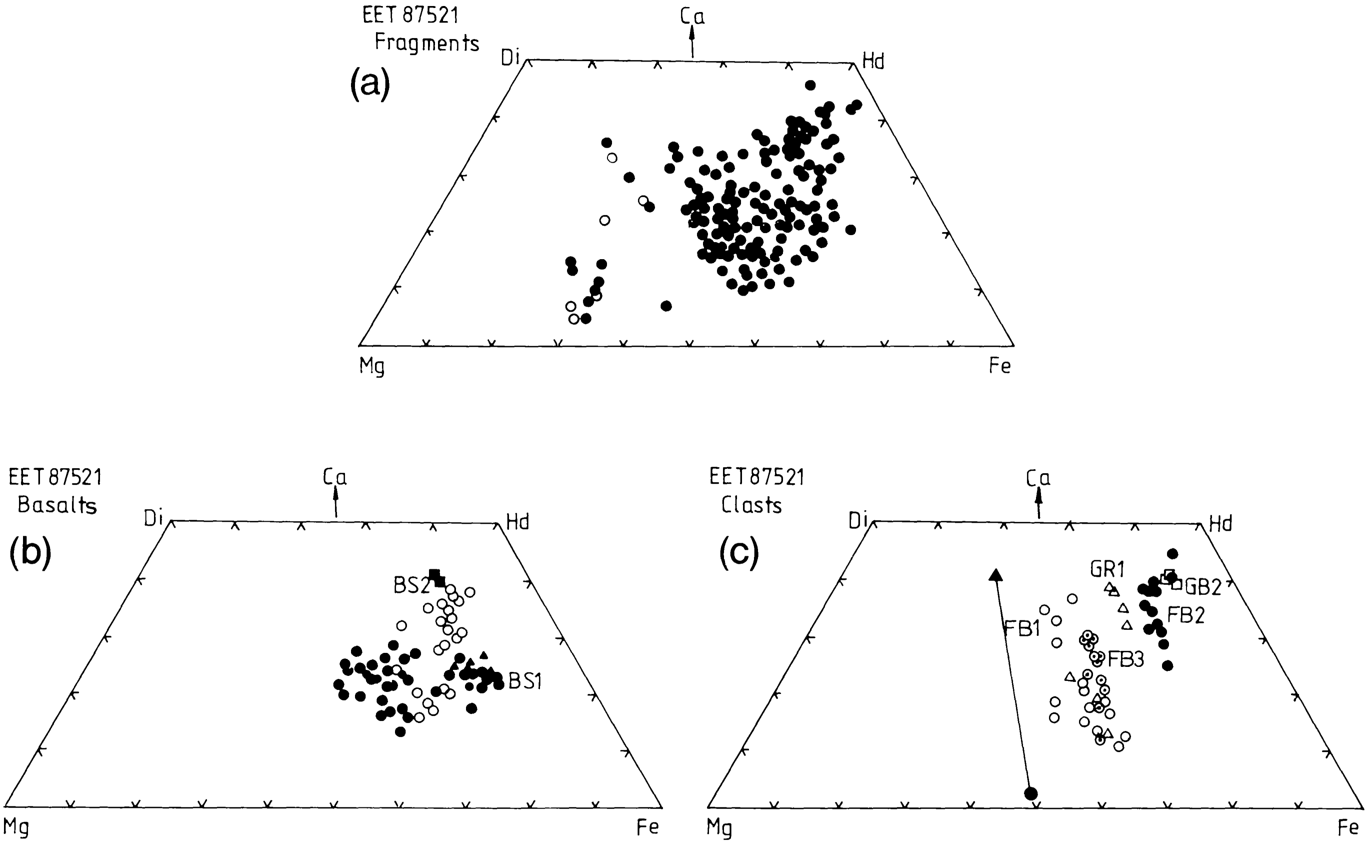

Fig. 2. Pyroxene compositions of EET87521. **(a)** Closed circles represent chemical compositions of pyroxene fragments. Open circles represent zoning trend of one Mg-rich crystal. **(b)** Closed circles represent zoning trends of basalt BS1. Solid squares, small circles, and triangles include pyroxenes in mesostasis of BS1. Open circles are those of basalt BS2. **(c)** Open triangles: pyroxenes in clast GR1; open boxes: pyroxenes in clast GB2; open circles: pyroxenes in clast FB1; closed circles: pyroxenes in clast FB2; circles with dots: pyroxenes in clast FB3. Symbols connected by the tie line show the exsolved pair analyzed by TEM.

TABLE 2. Chemical composition (wt%) of olivines and plagioclases in EET87521 and Y793274.

	EET87521					Y793274				
	Fa (BS1 meso)	Plag (BS1 core)	Plag (BS1 rim)	Plag (GB2 core)	Plag (GB2 rim)	Oliv (GB2 core)	Oliv (GB2 rim)	Plag (GB2 core)	Plag (GB2 rim)	Plag (BS2)
SiO_2	30.5	45.4	47.2	48.6	51.5	36.5	36.6	44.2	46.3	46.4
Al_2O_3	0.02	34.3	31.9	32.1	30.7	0.17	0.09	35.4	34.5	33.3
TiO_2	0.60	0.02	0.02	0.06	0.06	0.02	0.02	0.04	0.06	0.02
FeO	64.3	0.35	0.64	0.72	0.94	31.3	30.8	0.00	0.22	0.36
MnO	0.60	0.02	0.01	0.03	0.01	0.31	0.33	0.05	0.08	0.00
MgO	3.63	0.06	0.02	0.03	0.04	31.0	31.1	0.03	0.09	0.24
CaO	0.25	18.43	16.76	16.22	14.71	0.08	0.12	19.58	18.36	18.35
K_2O	0.01	0.03	0.19	0.09	0.21	0.00	0.00	0.05	0.07	0.13
Na_2O	0.05	0.92	1.66	2.20	2.80	0.00	0.00	0.42	0.90	1.04
Cr_2O_3		0.02	0.02	0.00	0.07	0.05	0.05	0.00	0.00	0.02
Total	100.0	99.6	98.4	100.1	101.0	99.5	99.2	99.8	100.7	99.9
Fo/Or*	9.2	0.2	1.2	0.5	1.2	63.9	64.3	0.3	0.4	0.8
Fa/Ab	90.8	8.3	15.0	19.6	25.3	36.1	35.7	3.7	8.1	9.2
An		91.5	83.8	79.9	73.5			96.0	91.5	90.0

*Mol%. Fo and Fa are for olivine and Or, Ab, An for plagioclase.

Fa: fayalite, Plag: plagioclase, Oliv: olivine, meso: mesostasis.
Names in parentheses are clast names in the text.

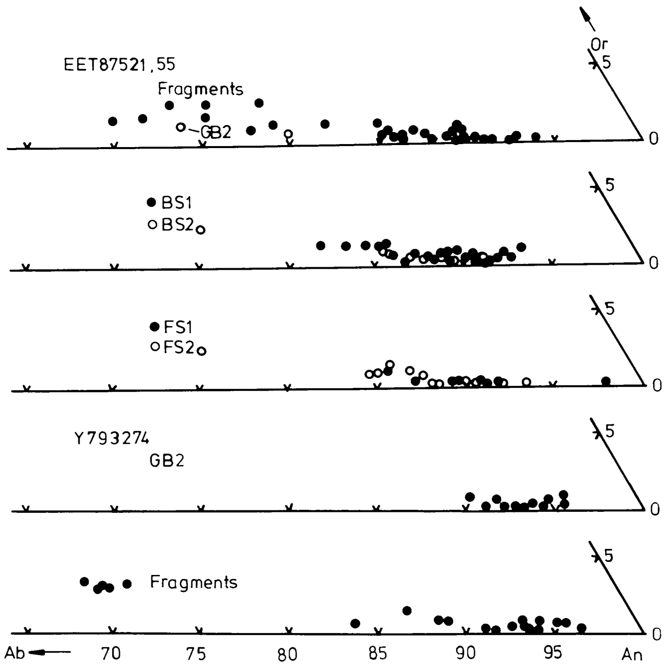

Fig. 3. A part of Or-Ab-An diagrams of plagioclases in fragments and clasts of EET87521 and Y793274. Numbers are An values.

TABLE 3. Spinel, ilmenite, and silica analyses (wt%) for EET87521 and Y793274.

	EET87521			Y793274
	Chromite (BS1 meso)	Ilmenite (BS1 meso)	Silica (BS1 meso)	Ilmenite (PI)
SiO_2	0.16	0.05	99.2	0.08
Al_2O_3	3.37	0.05	0.44	0.00
TiO_2	20.3	52.5	0.20	54.2
FeO	54.2	44.8	0.06	35.4
MnO	0.34	0.29		0.51
MgO	0.29	0.35	0.01	7.95
CaO	0.09	0.01		0.04
K_2O		0.00	0.23	0.03
Na_2O	0.05	0.03	0.04	0.03
Cr_2O_3	20.5	0.14		0.12
V_2O_3	0.66	1.09		0.34
Total	100.0	99.3	100.2	98.7

Names in parentheses are clast names in the text. Meso: mesostasis.

this transparent maskelynite-looking phase turned out to be a white glass with 16% FeO and 6% MgO. The Raman spectra of the white glass in GR1 show shocked plagioclase peaks. The chemical compositions of the mineral fragments in GR1 are the same as those in the matrices of other portions.

Possible highland rocks found in Y793274 in addition to the GR1 clast include clast(plagioclase)-laden glassy breccias, similar breccias with finely recrystallized matrix (Fig. 1e), and shocked plagioclase-rich clasts. As explained above, the GR1 clast is shock-melted breccia with fragments of mare pyroxenes, olivines, and plagioclase. Therefore, there is no mineralogical evidence that they are highland materials.

One gabbroic clast (GB2), 0.8 × 0.4 mm, consists of a rounded olivine 0.2 mm across, along with plagioclase and pyroxene (Fig. 1d; see also Fig. 2c of *Takeda et al.,* 1991). The modal abundances (oliv:pyx:plag) are about 1:3:3. Plagioclase is shocked and its An contents range from 96 to 89. The pyroxene is one of the most Mg-rich among the Y793274 pyroxenes (bulk: $Ca_{11}Mg_{61}Fe_{28}$) and its BEI and CMA show fine exsolution lamellae of augite ($Ca_{41}Mg_{45}Fe_{14}$) 1.2 μm wide with a 2.3-μm interval in the host ($Ca_4Mg_{65}Fe_{31}$) (Fig. 6). The width is larger than those of augites in pigeonites in many mare basalts (*Ghose et al.,* 1972), but is less than those of the highland plutonic pyroxenes (*Takeda et al.,* 1979). The olivine crystal (Fo_{65}) still preserves the zoning of CaO (Table 2).

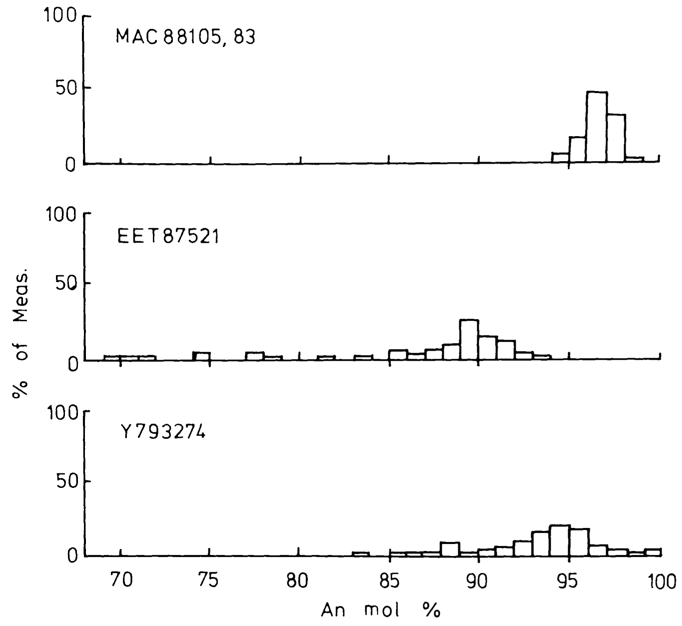

Fig. 4. Histogram of An content of plagioclase in EET87521, Y793274, and MAC88105.

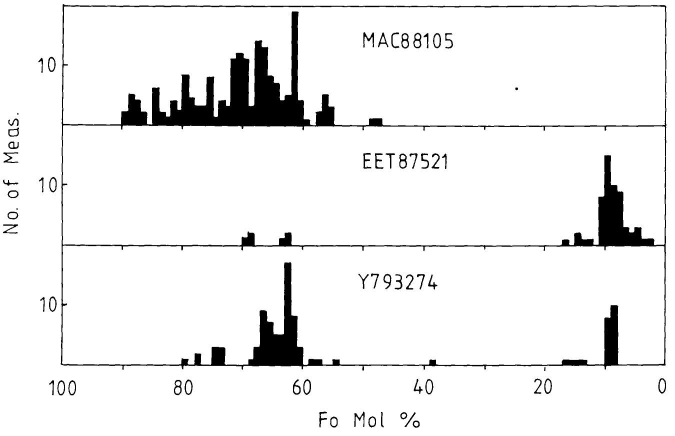

Fig. 5. Histograms of Fo content of olivines in EET87521, Y793274, and MAC88105.

Therefore, GB2 is not a plutonic rock. No lithic clast of apparent plutonic origin has been recognized in the PTS up to date. Inverted pigeonites, pyroxenes with coarse exsolution lamellae, or orthopyroxenes in granulites have not been found.

The most Mg-rich low-Ca pyroxene (opx) with Mg# = 80 was found in a small clast (PI) 0.3 mm in diameter with two joined lath-shaped ilmenite crystals (Fig. 1f) with high MgO contents (8 wt%, Mg# = 28), together with possible olivine (Tables 1 and 3; Figs. 6 and 7). Because of the small size, the textures and amounts of ilmenite do not unequivocally suggest that this clast is not a plutonic rock. Some other Mg-rich pyroxene (pigeonite) crystals show fine exsolution lamellae of augite detected by BEI and CMA.

There are no basaltic lithic clasts except for very fine-grained ones in the PTS (Fig. 1d), but dominant mare pyroxene components are found (*Takeda et al.,* 1991). The chemical zoning trends reconstructed by adding different zoning trends of many pyroxene fragments (Fig. 6) suggested that the original rocks are basalts similar to those found in the Apollo 16 breccias (*Takeda et al.,* 1990a,b). These mare pyroxene fragments are light to dark yellow, brownish, or pinkish in color,

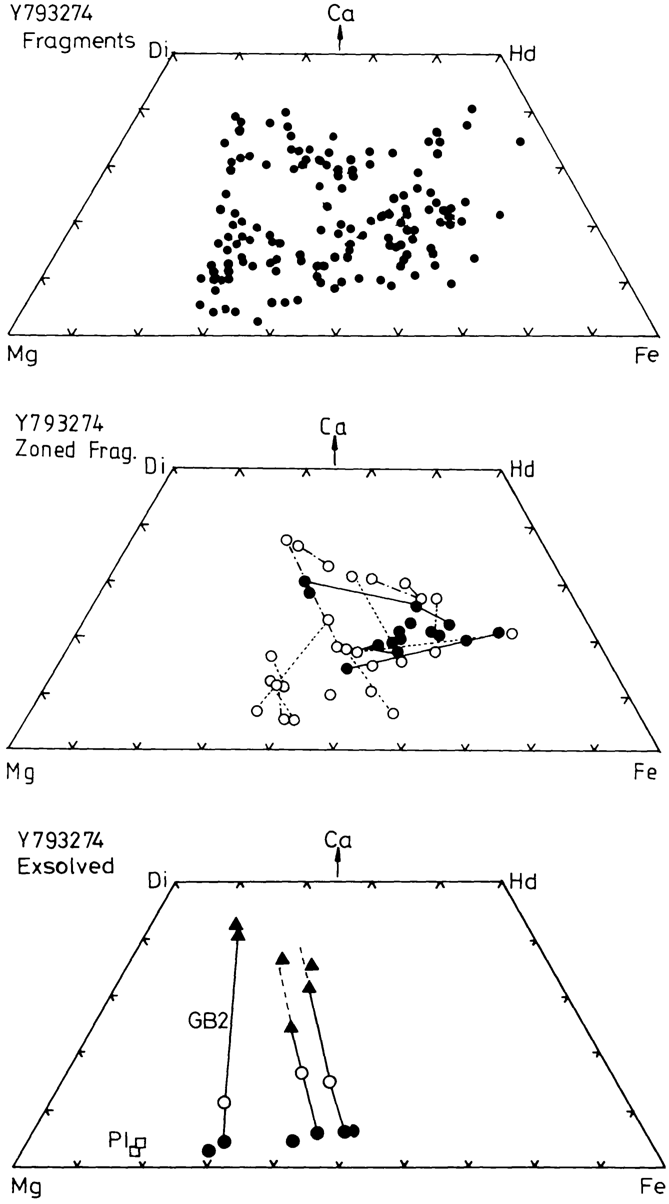

Fig. 6. Pyroxene quadrilateral of Y793274. Lines and dotted lines in zoned pyroxenes show zoning trend within one crystal. Solid circles in exsolved pyroxene: host composition; open circles: bulk composition; triangles: augite lamella. PI: pyroxene (opx)-ilmenite clast.

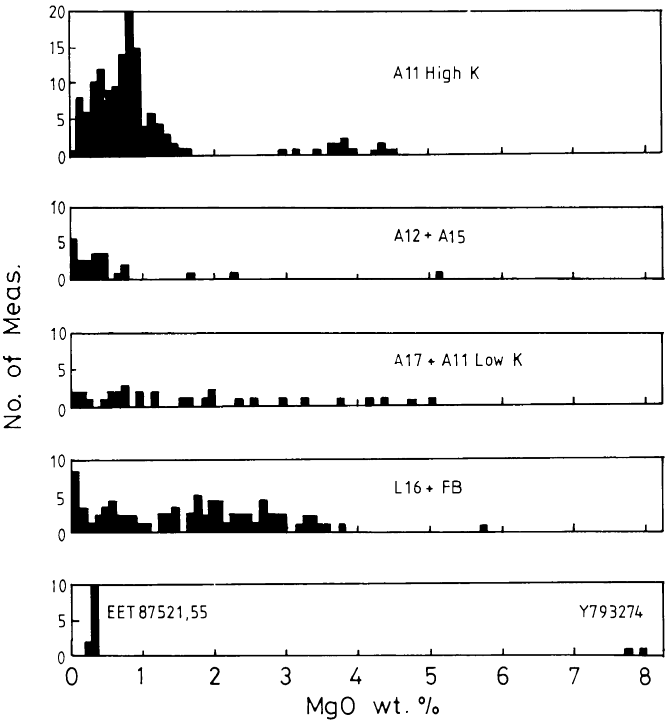

Fig. 7. MgO (wt%) content for ilmenites from major mare basalt group (*Papike et al.,* 1976), EET87521, and Y793274. A11, A12, A14, A15, A17, L16, FB represent Apollo 11, 12, 14, 15, 17, Luna 16, and feldspathic rocks in Apollo 12 and 14.

and individual crystals show chemical zoning (Fig. 6). Two fine crystalline basaltic clasts are present in the Y793274 PTS (Fig. 1d), but they contain far smaller pyroxenes than those found as fragments in the matrix. These crystalline clasts may be impact melt rocks.

The chemical compositions of all pyroxene fragments present in Y793274 are compared with those in lithic clasts and exsolved pyroxenes (Fig. 6). The chemical trends of the Y793274 pyroxene can be interpreted to be a combination of the zoning trends of quicky cooled lavas, and exsolved pyroxenes of different Mg# with limited Mg# range within one crystal. The most Mg-rich trend is the exsolution trend of GB2, whereas the Fe-rich trend is similar to those of BS1 in EET87521. The results suggest that the chemical variation is not due to the presence of many pyroxene types from different highland rocks that other lunar highland meteorites exhibited (*Takeda et al.,* 1990a,b). The presence of magnesian-exsolved pyroxenes with small ranges in Mg# suggests that they are early differentiated products of somewhat thicker lavas than those of the common mare basalts and the basaltic components represent a final crystallization part of the entire trend.

Fair amounts of Mg-rich olivines are found in Y793274 (Fig. 5), but again they are the same as those found in GB2 and may not be from plutonic rocks. The An contents of plagioclase fragments in Y793274 (Fig. 4) distribute more toward the Ca-rich side than those in EET87521 and have the maximum value at An_{95}. Contribution of the GB2 plagioclase to this value is large, while the plagioclases as in highland rocks (MAC88105) are minor.

Microtextures of Matrices

The microscopic features of matrices of EET87521 and Y793274 are similar. The TEM observation of Y793274 revealed that it is characterized by shock-produced melts of plagioclase, olivine, and clinopyroxenes, etc. The presence of shock-produced melts in the TEM scale (lower right half of the photo of Fig. 8a) are characteristics of Y793274. They are produced by melting of plagioclase, olivine, and clinopyroxene by impact. An olivine crystal in the upper left includes many dislocations, which are not recovered, suggesting that this specimen was not reheated after the impact.

An electron photomicrograph of plagioclase in Y793274 (Fig. 8b) shows that the crystal includes many glass lamellae produced by shock (gray parts running from upper right to lower left). This texture has been observed in some maskelynites. An electron photomicrograph of the Y793274 olivine (Fig. 8c) shows that many dislocations are produced in the crystal, part of which is converted into an amorphous state. The possibility of alteration in the Antarctic ice cannot be ruled out. Orthopyroxene also shows stacking faults.

Fine-grained matrices of EET87521 consist almost entirely of plagioclase and pyroxene. Recrystallization of the matrix is minor and not on a large scale. There is no evidence of maskelynitization of plagioclase to produce glass by a shock event. This fact indicates that this specimen did not experience a large shock event.

A pyroxene fragment in the matrix of EET87521,45 shows a TEM image of alternating lamellae of pigeonite and augite parallel to the (001) plane (Fig. 8d). The width of the augite lamellae is less than 1 μm and is about 300 nm on average. Stacking faults have been observed in the pigeonite host. Chemical compositions determined by the analytical TEM are $Ca_{2.4}Mg_{49.6}Fe_{48.0}$ for the pigeonite host and $Ca_{40.8}Mg_{35.2}Fe_{24.0}$ for the augite lamellae. This pyroxene is rather Mg-rich as a mare basalt and is consistent with a rapidly cooled nonplutonic origin for the Mg-rich pyroxenes.

DISCUSSION

The presence of considerable mare basalt components in EET87521 and Y793274 has been reported by *Delaney* (1989), *Warren and Kallemeyn* (1989), and a consortium group on Y793274 (e.g., *Kurat et al.,* 1990; *Takeda et al.,* 1990a; *Warren and Kallemeyn,* 1991). However, mineralogy of their highland components has not been well characterized.

Fe-rich Basaltic Components

The chemical trends of zoned pyroxenes of only the basaltic clasts in EET87521 (BS1) and some pyroxene fragments in Y793274 are similar and may represent those of initial crystallization from Fe-rich lavas. The trends are similar to those

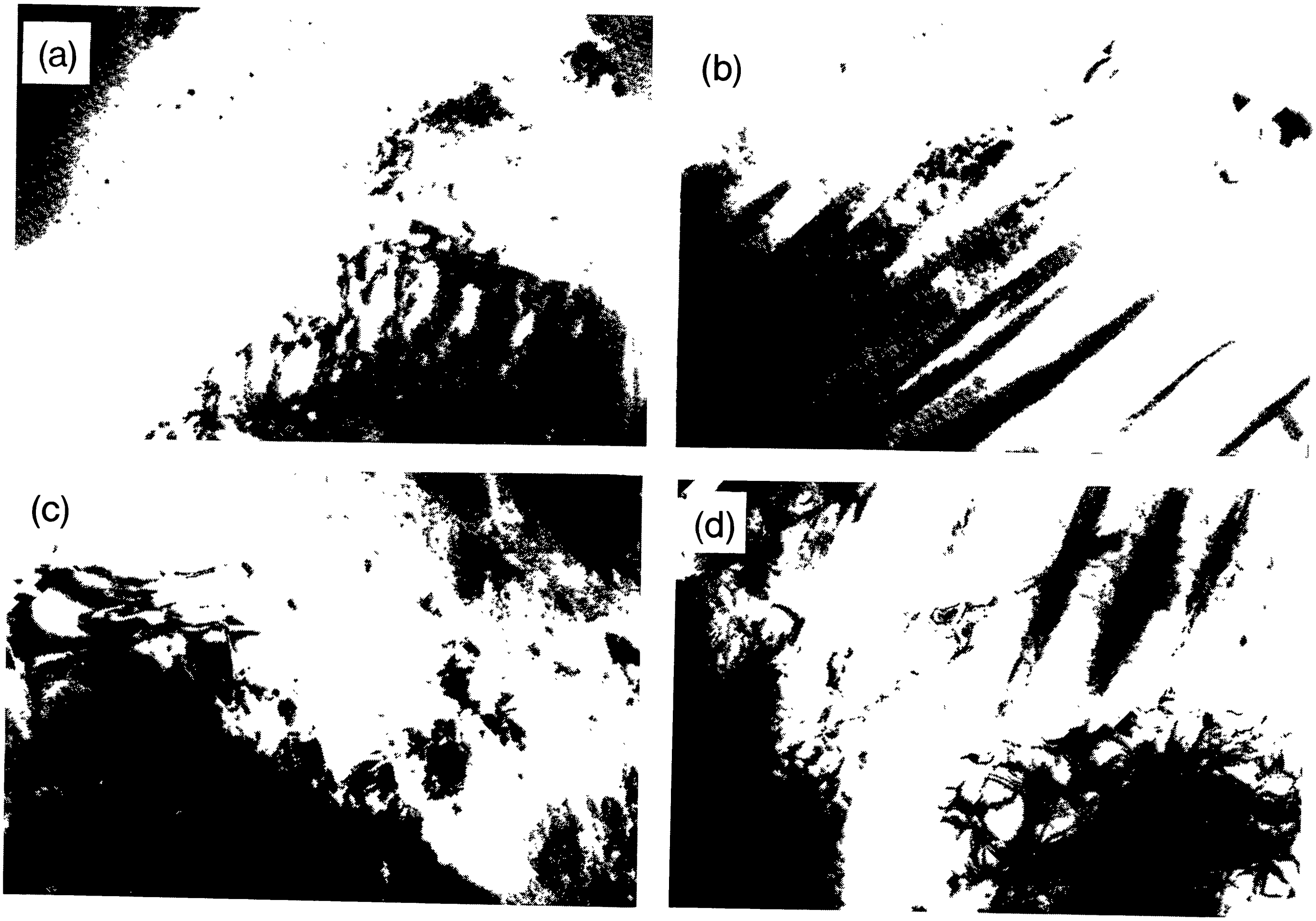

Fig. 8. Electron photomicrographs of Y793274 and EET87521. **(a)** The presence of shock-produced melts (upper left half of the photo) in matrix of Y793274. An olivine crystal in the lower right includes many dislocations, which are not recovered. Width is 1.8 μm. **(b)** Plagioclase crystal includes many glass lamella produced by shock (gray parts running from upper right to lower left). Width is 1.8 μm. **(c)** Many dislocations produced in an olivine crystal, part of which is converted into an amorphous state. Width is 1.5 μm. **(d)** Exsolution textures of the EET87521 pyroxene in the matrix. Width is 6.5 μm.

of pyroxenes such as reported for rare mare-rock clasts (Ba-2 in 60019) found in Apollo 16 breccias and Luna 16 (*Takeda et al.,* 1987), and the VLT clasts in lunar meteorites from the highlands (e.g., *Treiman and Drake,* 1983). The original rock is coarse grained, but is not a cumulate rock as reported for Asuka-31 (*Yanai,* 1991). The Apollo 16 pyroxene zonation trends are more Mg-rich than EET87521, but are similar to the Y793274 trend. The most Fe- and Ca-rich trend of EET87521 goes to that of hedenbergite in the HPF clast in Y791197 (*Takeda et al.,* 1986). The presence of such Fe-rich pyroxene and fayalite fragments in EET87521 and Y793274 suggests that these breccias sampled differentiated portions of the source lavas. The absence of exsolution lamellae observable by a microscope and the preservation of Fe-Ca zoning in fayalite also support a fast cooling in a shallow lava. A rock with fayalite, hedenbergite, silica, and Na-rich plagioclase can be reconstructed from the components in the matrix.

The discovery of a mesostasis portion in the BS1 clast in EET87521 provides us with useful information on the final differentiation process of this lava. The presence of ilmenite and Cr-Ti spinel in the mesostasis indicates that precipitation of Ti will take place even for a VLT basalt at the last stage of the small-scale differentiation. The coexistence of a silica mineral, fayalite mantling the ilmenite, and fine hedenbergite (Hd) with blebs of fayalite (Fa) implies that an Fe-rich low-Ca pyroxene was decomposed to fayalite and silica or that the immiscible liquids crystallized fine-grained Fa-Hd assemblage and silica or that all minerals were crystallized together.

The Cr-Ti spinel found in the mesostasis ilmenite is unique among lunar spinels because of its Cr-Fe-rich composition (Fig. 9). The chromian ulvöspinel reported in Asuka-31 (*Yanai,* 1991) is more Cr-poor, but the symplectite in it may be related to the mesostasis in EET87521.

Mg-rich Components

The Mg-rich pyroxenes with Mg# larger than about 50 in EET87521 have been considered to have been derived from the lunar highlands (*Delaney,* 1989). *Warren and Kallemeyn* (1989) detected Mg-rich pyroxenes in an EET87521 clast

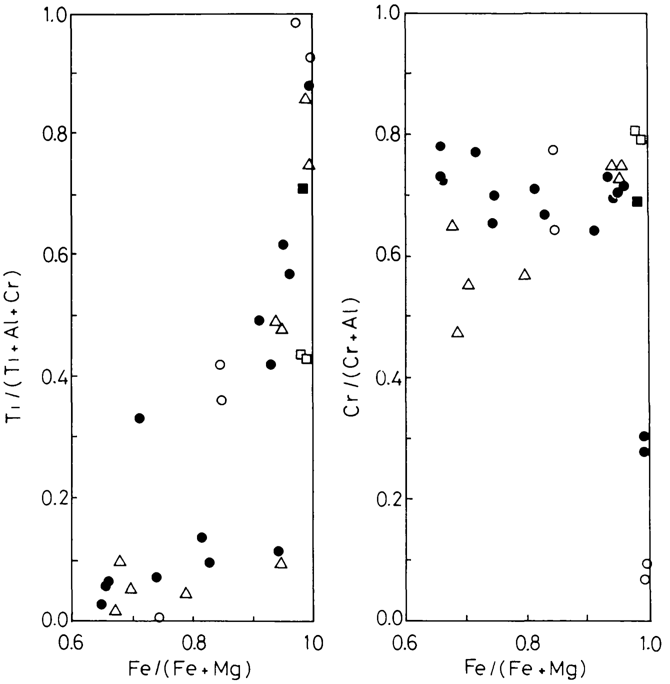

Fig. 9. (Ti/Ti+Al+Cr) vs. (Fe/Fe+Mg) variation diagrams for spinels from major mare basalt groups (*Papike et al.,* 1976), Asuka-31 (*Yanai,* 1991), and EET87521. Open squares: EET87521; solid squares: Asuka-31; open circles: Apollo 11 and 17; solid circles: Apollo 12 and 15; and triangles: Apollo 14 and Luna 16.

("H") that is clearly an anorthositic, fine-grained impact melt of highland derivation. However, they were not found in plutonic rocks of the early lunar crust or granulitic rocks common in lunar meteorites from the highlands. Plagioclase-rich impact-derived rocks such as those described by *Warren and Kallemeyn* (1989) are difficult to identify as highland rocks on the basis of the pyroxene mineralogy. In addition to the evidence cited by *Warren and Kallemeyn* (1989), such as the texture, the mode, the silicate solid-solution compositions, and the presence of compositionally "meteoritic" FeNi metals, *Warren and Kallemeyn* (1991) have noted that the high Ti/Cr ratios of the pyroxenes in this clast confirm that it is not of VLT or even low-Ti mare derivation. They concluded that it hardly seems likely to be of high-Ti mare derivation, so it must be of highland derivation. We use exsolution and inversion textures as a clue to identify plutonic pyroxene as the first step to find highland rocks. All the Mg-rich pyroxenes we found in EET87521 and Y793274 show either fine exsolution lamellae with widths less than a few micrometers or chemical zoning as was found in the Ba-2 clast in 60019 (*Takeda et al.,* 1987). One pyroxene examined by TEM has augite lamellae 300 nm wide.

The most Mg-rich zonation trend of the basaltic pyroxenes in a lava may extend to Mg# greater than 60 as in Y793274, Y793169 (*Yanai and Kojima,* 1987b), and Apollo 16 basalts. The GB2 clast found in Y793274 contains a pyroxene with fine exsolution and Mg# more Mg-rich than the above limit of Mg# for the basaltic rocks. The plagioclase crystals show chemical zoning due to the original crystal growth. There are other clasts (GB1) with similar pyroxene and minor plagioclase. Their limited ranges of Mg# and pyroxene exsolution suggest that they are intermediate between lavas and plutonic rocks. They may be early crystallized components in fairly thick lavas. Assuming that Y793274 is a breccia derived from a limited region on the lunar surface, we suggest the following hypothesis. The presence of similar pyroxenes with Mg# between GB2 and the VLT basalts suggests that crystallization of a GB2-like rock is related to more differentiated Fe-rich lavas, the solidification of which will produce VLT-like basalts.

The most Mg-rich lithic clast (PI) contains pyroxene (opx) and ilmenite and possibly olivine. If this clast is the earliest crystallization product from the same thick lava that crystallized the GB2 clast, some amounts of ilmenite may have been removed from a primary magma by disequilibrium growth of ilmenite from supercooled magma because the PI clast contains an appreciable amount of ilmenite with the highest MgO content (8 wt%) among the lunar ilmenites (Fig. 7) and the PI pyroxene is the most Mg-rich of the Y793274 pyroxenes. It is difficult to show that the VLT magma is a residual differentiated magma after removal of ilmenite, pyroxene, and other phases and removal of the GB2-like components. This hypothesis suggests that the parent magma(s) for Y793274 clasts (GB2 and PI) was something more Ti- and Mg-rich than "VLT-like," and that it began crystallization with pyroxene plus ilmenite and some other phases as liquidus phases. However, the high ratios of ilmenite to other phases in these clasts are of very dubious significance, considering that the modes are based on tiny clasts containing just a few grains of each phase. Further studies are required to obtain trace-element chemistry to prove or disprove this hypothesis.

The bulk chemistry of Y793274 indicated mixing of the VLT basalt and the highland regoliths (*Warren and Kallemeyn,* 1991). This interpretation is mainly based on the fact that Y793274 contains intermediate contents of Al_2O_3 (19 wt%). Although we searched for plagioclase-rich lithic clasts in Y793274 and EET87521, many of them are plagioclase-rich basalts except for the H clast described by *Warren and Kallemeyn* (1989). If there are many highland plagioclases in Y793274 and EET87521, as there are in MAC88105, there should be more Ca-rich components (Fig. 4).

Matrix Materials

Shock-produced glasses are often observed in matrix glasses and plagioclase crystals of Y793274 and EET87521. The olivine crystal in Y793274 (Fig. 8a) shows numerous dislocations, and no recovery was observed. The facts suggest that this sample has never reheated after the shock event. This shock event can be attributed to that of ejection from the lunar surface, but the shock event at the lunar surface can also produce such glasses, which will be kept on a cold brecciated lava surface until the ejection. Many other lunar meteorites from the highlands did not keep records of the shock events that ejected them to the Earth.

SUMMARY

The question why only the VLT-type basaltic fragments were found in lunar meteorites, regardless of whether they are derived from lunar highlands or mare areas, requires further studies. Whether the VLT bulk compositions represent an initial source composition or differentiated one is not clear at present. Frequent association of VLT-type basalts with lunar meteorites tends to imply that the lavas originate close to the lunar highlands from where many lunar meteorites were derived. Some of our new findings are summarized as (1) main Fe-rich basalts in EET87521 and Y793274 contain differentiated products; (2) Mg-rich components such as a gabbroic clast in Y793274 are not plutonic rocks of the early lunar crust, but are early crystallized components of thicker lava flows than those of common mare basalts; (3) a pyroxene crystal in EET87521 shows exsolution lamellae of augite 300 nm wide, which is compatible with a quickly cooled lava origin; (4) a magnesian ilmenite-pyroxene-bearing rock found in Y793274 may be the earliest crystallization product; and (5) shock microtextures by TEM show that Y793274 has never been reheated after the shock event.

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