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MINERALOGICAL STUDIES OF LUNAR METEORITE YAMATO-793169, A MARE BASALT

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Abstract: A preliminary mineralogical study of the lunar meteorites Yamato (Y)-793169 and Asuka (A)-881757, which were apparently derived from a mare region of the Moon, has been performed to identify crystallization trends of their pyroxenes. Y-793169 is a crystalline basalt with similar basaltic components to lunar breccias EET87521 and Y-793274, containing strongly zoned Fe-Ca-rich pyroxenes. Their zoning trends in the pyroxene quadrilateral are closest to those found in the basaltic clast in an Apollo 16 breccia. Differentiation trends expressed by Ti/(Ti + Cr) *versus* Fe/(Fe + Mg) of Y-793169 and A-881757 pyroxenes are similar but they differ from those of EET87521. The Y-793169 trend starts at a more Mg-rich composition point than the A-881757 trend. Based on differences in textures and ranges of zoning trends, the pyroxene of A-881757 could represent growth deeper in the lava unit under conditions more closely approaching equilibrium, than Y-793169, which appears to have formed from a lava flow of similar bulk composition. Although Y-793169 has been described as the VLT basalt, some mesostases contain significant amounts of ilmenite and ulvöspinel, together with fayalite, troilite, chromite and a silica mineral. Mg-rich pyroxenes as found in Y-793274 and EET87521 are not present in Y-793169 and A-881757 basalts.

1. Introduction

All early recognized lunar meteorites before 1989 were highland breccias (WARREN and KALLEMEYN, 1991), but later finds were not. Four lunar meteorites, EET87521, Y-793274, Y-793169, and A-881757 (Asuka-31) have been proposed to be samples of mare regions of the Moon (DELANEY, 1989; WARREN and KALLEMEYN, 1989; YANAI, 1991; TAKEDA *et al.*, 1991). EET87521 and Y-793274 are breccias rich in lunar mare components (DELANEY, 1989; WARREN and KALLEMEYN, 1989; TAKEDA *et al.*, 1992). Y-793169 has originally been described as a eucrite-like meteorite, because it is composed of Fe-rich pigeonite and plagioclase (YANAI and KOJIMA, 1987). However, the compositional trends of its pyroxenes differ from that of eucrites (TAKEDA and GRAHAM, 1991). As part of a preliminary consortium study, we studied Y-793169 and A-881757 by mineralogical techniques, including electron probe microanalysis, and compared them with basaltic components in mare breccias EET87521 and Y-793274 and with Apollo and Luna mare basalts (PAPIKE *et al.*, 1976).

By combining information on Y-793169 and A-881757 reported by other members of the consortium group (KOEBERL *et al.*, 1993; NISHIIZUMI *et al.*, 1992; WARREN and

KALLEMEYN, 1992), we propose that these two basalts may be related and are distinct from other mare basalts although their pyroxene zoning trends are closest to those of rare mare rock clasts in Apollo 16 highland breccias (TAKEDA *et al.*, 1987) and the VLT's (TREIMAN and DRAKE, 1983).

2. Samples and Experimental Techniques

We investigated polished thin sections (PTS) A-881757,51-4 (Asuka-31) and Y-793169,51-3 supplied by the National Institute of Polar Research (NIPR). Both samples were allocated as parts of two consortium studies. Mineral chemistries and textures 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. Chemical analyses were made with 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). The acceleration voltage was 15 kV and beam current was 12 nA on a Faraday cage. For the pyroxene Ti/(Ti+Cr) *vs.* Fe/(Fe+Mg) plots, measurements were made three times (3×10 s) and averaged for one point analysis.

We also measured Mg-Fe-Ca chemical zoning profiles of pyroxenes in these basalts with a JEOL EPMA (JCXA-733) at Ocean Research Institute, University of Tokyo. The measuring conditions are the same as reported previously (TAKEDA *et al.*, 1992). We measured zone profiles selected on color maps produced by the PXQUAD system (SAIKI *et al.*, 1992). Modal abundances of minerals in Y-793169 were obtained from colored back scattered electron (BSE) image of SEM for a particular mineral by a computer. The abundances of minerals with a similar BSE intensity (ilmenite and ulvöspinel) were obtained by point analysis for every $0.5 \times 0.5\ mm^2$ area.

3. Results

3.1. Y-793169

The Y-793169,51-3 PTS is a crystalline subophitic basalt with Fe-rich pyroxene, plagioclase and dark mesostasis portions (Fig. 1). Fractures in pyroxene crystals and partly maskelynitized plagioclase crystals indicate shock effects, but the overall texture is not disturbed. Some of dark mesostasis materials are converted into dark glassy materials. The pyroxene crystals are similar to chemically zoned pigeonites in eucrites (TAKEDA and GRAHAM, 1991) and reach up to 3×1 mm in size. The plagioclase crystals show lath shapes and their sections perpendicular to the elongated direction (up to 1.0×0.5 mm in size) often show rhombic shapes. In two areas aggregates of plagioclase are present. Also the plagioclase crystals show extensive chemical zoning. Modal abundances of minerals are: pyroxene 56 vol%, plagioclase 42%, ilmenite 1%, and ulvöspinel 1%.

Chemical composition of pyroxene in the PTS is shown in the pyroxene quadrilateral (Fig. 2) and in Table 1. The Fe-Mg-Ca zoning varies between mg number $= 100 \times Mg/(Mg+Fe) = 60$ and the Fe-rich composition toward the Ca-Fe join. Pyroxenes in Y-793169 show a similar chemical trend to those in basaltic clasts of

Fig. 1. Photomicrograph of the Y-793169,51-3 PTS. Width is 5 mm.

Table 1. Chemical compositions (wt%) of pyroxenes in Y-793169.

	Mg-rich core	Rim	Fe-rich rim	Hedenbergite
SiO_2	51.8	49.5	48.0	45.9
Al_2O_3	0.94	2.05	1.19	2.39
TiO_2	0.40	1.05	0.82	0.66
FeO	21.1	17.8	33.4	35.1
MnO	0.47	0.30	0.63	0.43
MgO	18.90	11.66	6.21	1.55
CaO	5.39	16.08	9.25	13.51
Na_2O	0.00	0.01	0.00	0.10
Cr_2O_3	0.52	0.68	0.05	0.06
V_2O_3	0.00	0.04	0.04	0.01
Total	99.52	99.17	99.59	99.71

EET87521 and fragments in the matrix of Y-793274 (TAKEDA *et al.*, 1992). One typical zoning trend (Fig. 2a) is from Mg-rich core $Ca_{10}Mg_{55}Fe_{35}$ to Ca-rich mantle with nearly constant Mg/(Mg + Fe) ratios. Another trend (Fig. 2b) is from Ca-poor, Mg-rich core ($Ca_{12}Mg_{52}Fe_{36}$) with initially increasing Ca, to intermediate Ca, Fe-rich portion and then shows Fe-enrichment with nearly constant Ca contents towards the mesostasis portion. Two other trends (Figs. 2c, d) are combination of the above two trends observed in other crystals. The most Fe-rich composition almost reaches the Ca-Fe join. Although very fine exsolution-like textures are found in some pyroxenes microscopically, the EPMA traverses did not show the chemical separation.

The An-contents of plagioclase crystals range from 96 to 85 (Fig. 3; Table 2). Mesostasis consisting of ilmenite, ulvöspinel, fayalite, a silica mineral, troilite and chro-

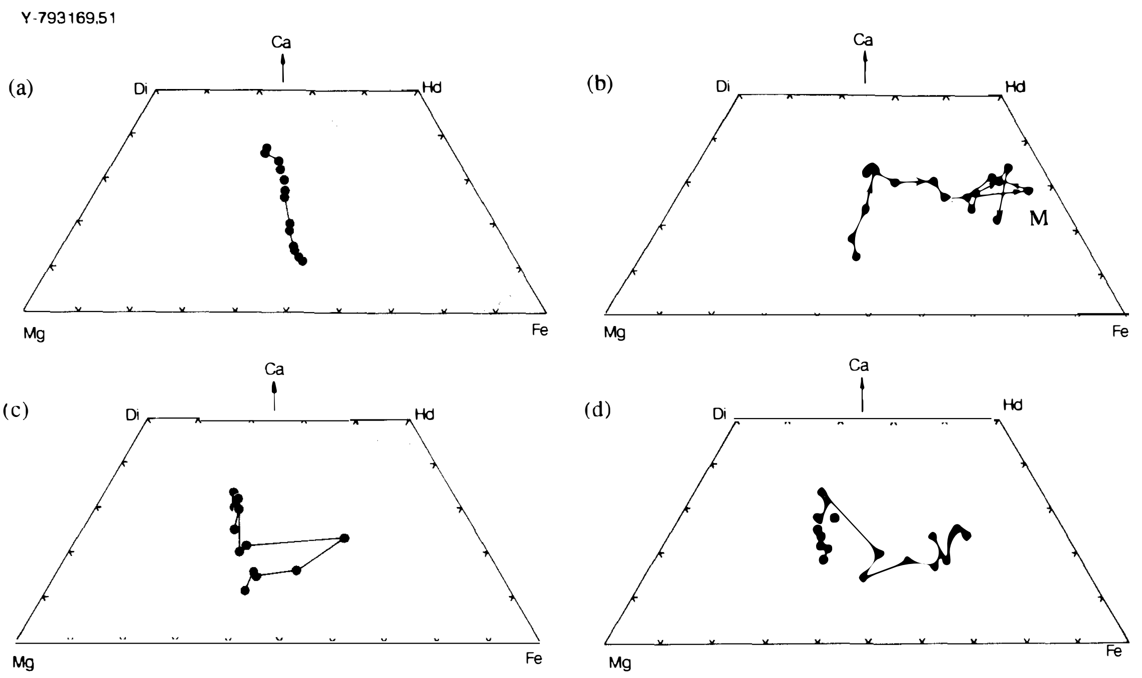

Fig. 2. Pyroxene quadrilaterals of Y-793169, showing chemical variations of some typical zoning trends. Subnumbers (a–d) refer to different single crystals. M: Mesostasis

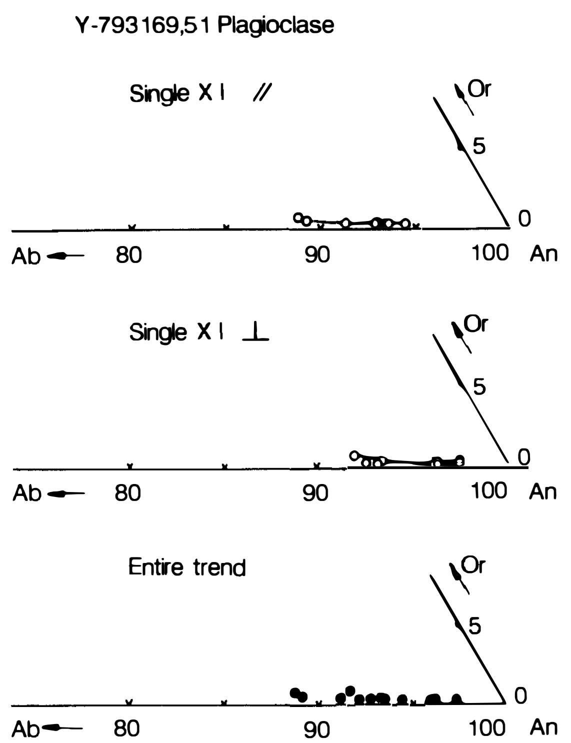

Fig. 3. A part of Or-Ab-An diagrams of plagioclase of Y-793169. Numbers are An and Or values in mole %.

mite is present in places adjacent to Ca, Fe-rich pyroxene and Na-rich plagioclase. Some of the mesostases consist of glass which is rich in Fe and Ca but poor in alkalis (Table 2). Chemical compositions of ilmenite and ulvöspinel in the mesostasis por-

Table 2. Chemical composition (wt%) of plagioclases and mesostasis in Y-793169.

	Core	Rim	Mesostasis
SiO_2	45.3	47.1	50.0
Al_2O_3	33.9	32.4	10.1
TiO_2	0.05	b.d.	2.38
FeO	0.40	0.83	22.4
MnO	b.d.	b.d.	0.40
MgO	0.21	0.06	0.87
CaO	18.78	17.61	11.99
Na_2O	0.61	1.02	0.30
K_2O	0.03	0.10	0.63
Total	99.28	99.12	99.07

b.d.: below detection.

Table 3. Ilmenite and spinel analyses (wt%) for Y-793169, A-881757, and EET87521.

	Ilmenite			Ulvöspinel	Chromite
	Y-793169	A-881757*	EET87521	Y-793169	Y-793169
SiO_2	—	0.05	0.05	0.00	0.00
Al_2O_3	0.12	0.23	0.05	1.94	15.41
TiO_2	52.7	50.5	52.5	32.0	4.92
FeO	45.4	47.1	44.8	60.4	31.9
MnO	0.42	0.29	0.29	0.33	0.30
MgO	0.11	0.45	0.35	0.29	2.94
CaO	0.06	0.06	0.01	0.04	0.04
Na_2O	0.00	0.02	0.03	0.00	0.02
Cr_2O_3	0.00	1.02	0.14	3.50	41.0
V_2O_3	0.00	—	1.09	0.00	0.53
Total	98.81	99.72	99.31	98.50	97.06

* After YANAI (1991).
Data are single analysis.

tion are Fe-rich (Table 3). Although this basalt has been classified as a VLT basalt (YANAI, 1991), the amounts of ilmenite and ulvöspinel in the mesostasis are fairly large (*ca.* 2 vol%).

The Cr-Ti-Fe spinel found in the mesostasis ilmenite in EET87521 (TAKEDA *et al.*, 1992) has been found also in Y-793169, adjacent to Cr-bearing ulvöspinel (Table 3). The chromian ulvöspinel reported in Asuka-31 (Yanai, 1991) is more Cr-poor than that in EET87521. These spinels are unique among lunar spinels because of their Cr-Fe-rich composition.

3.2. *A-881757*

Mineralogy of A-881757 (Asuka-31) has been described previously in detail (YANAI,

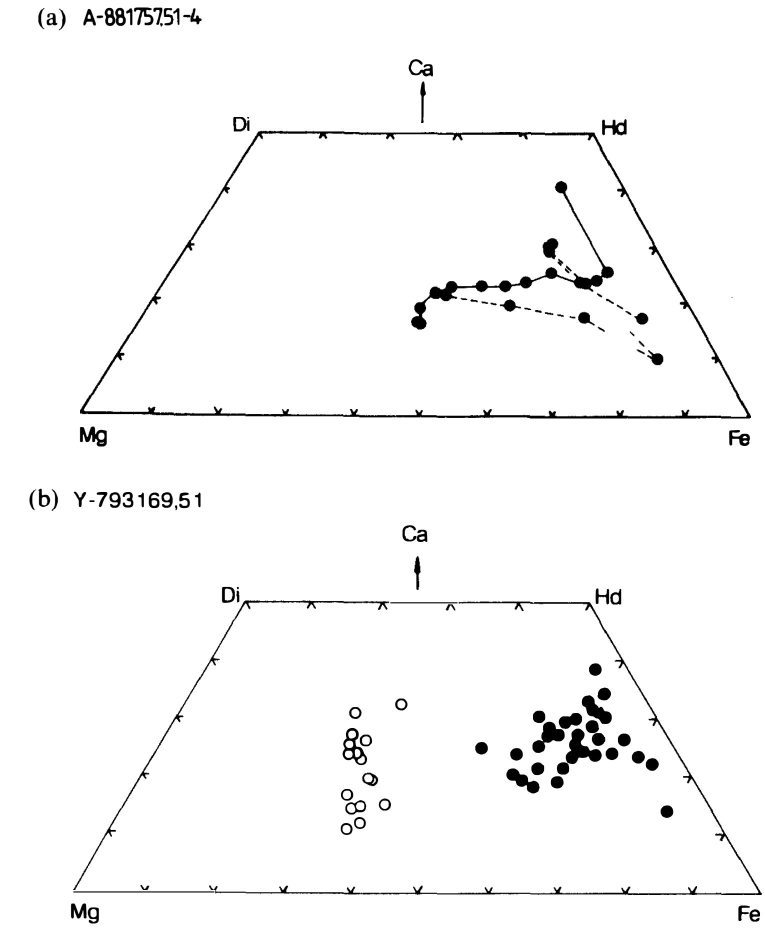

Fig. 4. (a) Pyroxene quadrilateral of A-881757 (present study), showing more Fe-rich trend than that of Y-793169. The circles connected by lines represent one traverse. (b) Summary of Y-793169 data. Open circles are Mg-rich cores and solid circles are Fe-rich areas.

1991). The rock is more coarse-grained and equigranular than Y-793169, with crystal sizes between 2–4 mm. This sample has been described as gabbro (YANAI, 1991). Evidence of coarse exsolution or inversion of pigeonite to orthopyroxene has not been detected by EPMA. The pyroxene cores are more Fe-rich than that of Y-793169 (Fig. 4), and are similar to those in the large basaltic clasts of EET87521 (TAKEDA *et al.*, 1992). Among the individual trends, the Fe-enrichment trend with nearly constant Ca are common (Fig. 4). Crystals approaching the mesostasis display the trend towards hedenbergitic composition. Note that the range of A-881757 is smaller than that of Y-793169 and that the first composition to crystallize of Y-793169 is more Mg-rich than that of A-881757 (Fig. 4).

Although this sample is classified as a VLT basalt, abundant dark mesostasis portions contain fair amounts of ilmenite (6 vol%). It is difficult to give a good estimate of the ilmenite abundance because of its very coarse-grained texture. The Cr-Ti-Fe spinel associated with ilmenite in EET87521 and Y-793169 was detected in this sample (YANAI, 1991). The symplectite texture reported by YANAI (1991) is similar to the texture of the mesostasis portion in EET87521 (TAKEDA *et al.*, 1992).

4. Discussion

4.1. Crystallization trends of pyroxenes

The chemical trends of zoned pyroxenes in Y-793169 and A-881757 and those of the basaltic clasts in EET87521 (BS1) and some pyroxene fragments in Y-793274 are similar and may represent crystallization from similar Fe-rich lavas. The trends represented by Fig. 2b (Ca-poor, Mg-rich core to intermediate Ca, Fe-rich, to Ca-rich and Fe-rich) are unusual but are similar to those of pyroxenes such as reported for rare mare-rock clasts (Ba-2 in 60019) found in Apollo 16 highland breccias and Luna 16 (TAKEDA *et al.*, 1987), and some of the VLT clasts in lunar meteorites from the highlands (*e.g.*, TREIMAN and DRAKE, 1983).

All the clasts of the VLT basalts reported up to date (TREIMAN and DRAKE, 1983) are small fragments, and their zoning trends may not be representative. Because both Y-793169 and A-881757 are fairly large crystalline rocks, the zoning trends can provide more complete pictures of chemical variations during crystal growth unless subsequent homogenization modified their trends. The Y-793169 trends represent more Mg-rich trend than those of A-881757 and the basaltic clast in EET87521. The Apollo 16 pyroxene zonation trends are similar to the Y-793169 and Y-793274 trend. A composition approaching to hedenbergite found in EET87521 is also present in the HPF clast in Y-791197 (TAKEDA *et al.*, 1986). These trends of the VLT basalts and of Y-793169 and A-881757 are different from those reported for known mare basalts (PAPIKE *et al.*, 1976). Because a possibility of these two rocks being low-Ti basalt cannot be ruled out, we compared these trends with those of Apollo 12 and 15 low-Ti basalts. However, the low-Ti basalt trends are different from those of the two rocks. In addition, the Apollo 12 and 15 basalts contain large phenocrysts of pigeonite in fine-grained matrices of pyroxene and plagioclase (PAPIKE *et al.*, 1976).

The A-881757 rock is coarse-grained, but is not a cumulate gabbroic rock as reported for Asuka-31 (YANAI, 1991). A-881757 does not show a cumulate texture known for the cumulate eucrites. Cumulate gabbroic rocks normally show nearly homogeneous chemistry of pyroxene and plagioclase and often show coarse exsolution texture and inversion to orthopyroxene, as expected from near equilibrium crystal growth and slow subsolidus cooling in the cumulate environment. The absence of coarse exsolution lamellae in both Y-793169 and A-881757 observable microscopically suggests a cooling origin in a lava not as slow as in cumulate eucrites. This observation is in line with the presence of extensive zoning in their pyroxenes.

A rock with fayalite, hedenbergite, silica, and Na-rich plagioclase (An_{73}) has been reconstructed from the components in the matrices of EET87521, Y-793274 and Y-791197. However, compositions of plagioclase in Y-793169 (Fig. 3) are not as Na-rich as those in EET87521 and Y-793274 (TAKEDA *et al.*, 1992). This hypothetical rock may be the final differentiated product of a lava or a part of crystallized mesostasis. The discovery of a similar mesostasis portion in Y-793169 to that in the BS1 clast in EET87521 provides us with useful information on the final differentiation process of this lava. The coexistence of isolated grains of a silica mineral, fayalite and ilmenite or ulvöspinel in Y-793169, implies that fayalite and silica crystallized together at the final stage. Similar assemblages with fine-grained ropy shapes and hedenbergite found in EET87521 have been interpreted as late-stage decomposition products of Fe-rich metastable pyroxene (TAKEDA *et al.*, 1992). The symplectite in the mesostasis portions of A-881757 may be related to the mesostasis in EET87521.

4.2. Ti/(Ti+Cr) vs. Fe/(Fe+Mg) trends

The Ti/(Ti+Cr) ratio is a useful fractionation indicator as Ti is incompatible and Cr is compatible in pyroxene, and when coupled with Fe/(Fe+Mg), has been used to discuss crystallization trend of mare basalts (NIELSEN and DRAKE, 1978).

BOESENBERG and DELANEY (1992) showed that pyroxene in the EET87521 VLT lithic clasts falls into two distinct groups. Group A contains pyroxenes in lithic clasts with low Fe/(Fe+Mg) ratios ranging from 0.28 to 0.6 and Ti/(Ti+Cr) ratios varying from 0.1 to 0.7. Group B has pyroxene with Fe/(Fe+Mg) ratios between 0.55 and 0.85 and Ti/(Ti+Cr) ratios between 0.4 and 1.0 (Fig. 5). On the other hand, the Luna 24 and Apollo 17 compositional data (VANIMAN and PAPIKE, 1977) show almost complete overlap with no clear split between the two groups.

Y-793169 contains pyroxenes with low Fe/(Fe+Mg) ratios from 0.37 to 1.0 and Ti/(Ti+Cr) ratios varying from 0.42 to 0.9 (Fig. 5). A-881757 pyroxenes have Fe/(Fe+Mg) ratios between 0.48 and 0.91 and Ti/(Ti+Cr) ratios between 0.53 and 0.92 (Fig. 5). The slopes of the trends of Y-793169 and A-881757 are similar and fall in between those of Apollo-15 low-Ti basalts and Apollo-17 VLT of NIELSEN and DRAKE (1978) and the trend may be compatible with the observed crystallization trends for low-Ti lunar basalts. These trends appear to reflect near surface crystallization of the two lavas because of their similar slopes. The Y-793169 trend begins in the middle of Group A trend of EET87521 and reaches the middle of Group B trend and changes the slope to follow the general trend. The A-881757 pyroxene trend begins in between

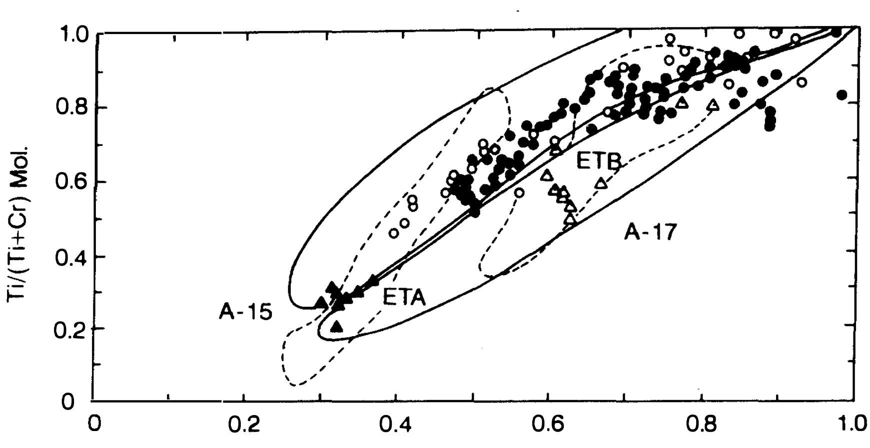

Fig. 5. Ti/(Ti+Cr) vs. Fe/(Fe+Mg) mol ratios for pyroxenes in Y-793169. Data from A-15 mare basalts and A-17 VLT basalts are from NIELSEN and DRAKE (1978). Open circles: Y-793169; solid circles: A-881757. ETA and ETB represent Groups A and B of EET87521 (BOESENBERG and DELANEY, 1992). Triangles (filled: Mg-rich and open: Fe-rich): Our data of EET87521.

Groups A and B of EET87521.

A sudden decrease of the Ti/(Ti+Cr) ratio in a fractionating magma is only plausible if a Ti-rich phase such as ilmenite began to precipitate when the fractionating magma reached this composition. BOESENBERG and DELANEY (1992) stated that as the clasts in EET87521 have very low Ti contents, a Ti-rich phase is extremely unlikely to enter the fractionation sequence. The VLT magmas seem unlikely candidates to precipitate Ti-rich oxides as they have the lowest Ti and hence require extensive fractionation to become ilmenite saturated.

However, Y-793169 and A-881757 precipitate fair amounts of ilmenite and ulvöspinel at later stage of crystallization. Even if less titaniferous mare basalts are considered, the effect of increasing Ti flattens the Ti/(Ti+Cr) *vs.* Fe/(Fe+Mg) trend at the later stage, presumably because equilibration with ilmenite or another Ti-rich phase, inhibits the increase of Ti/(Ti+Cr) in pyroxene. The trend of A-881757 with Fe/(Fe+Mg) larger than 0.7 is flatter. BOESENBERG and DELANEY (1992) suggest that the two groups of EET87521 (Fig. 5) represent the fractionation of different lavas that had different original Ti/(Ti+Cr) ratios, and/or different Fe/(Fe+Mg) ratios.

In addition to the pyroxene trend described, BOESENBERG and DELANEY (1992) also proposed that olivine fractionation can modify the Fe/(Fe+Mg) ratio of the source magma of these lithic clasts. The Mg-rich gabbroic clasts with olivine present in Y-793274 and the Mg-rich pyroxenes of Y-793274 and EET87521 are found mainly as individual fragments with little chemical zoning (TAKEDA *et al.*, 1992). However, the zoning trend of EET87521 Group B pyroxenes is mostly within one crystal or within the single lithic clast. It should be remembered that unlike EET87521 and Y-793274, Y-793169 and A-881757 are not polymict breccias. The fractionation trends of Y-793169 and A-881757 are definitely those of crystal growth during the solidification of the lavas.

4.3. Relationship between A-793169 and A-881757

A detailed comparison of their pyroxene crystallization trends of these two meteorites with those of lunar low-Ti basalts and the VLT ones recovered by the Apollo and Luna missions showed their affinity to VLT, in spite of their higher TiO_2 concentration (TiO_2 for A-881757 is 2.5 wt%) reported by WARREN and KALLEMEYN (1992) than previously known and the presence of fair amounts of ilmenite (or ulvöspinel) of these two rocks. The higher TiO_2 contents are consistent with the presence of fair amounts of ilmenite and ulvöspinel in these two rocks. The presence of ilmenite in the mesostasis of all these lunar basaltic meteorites indicates that precipitation of a Ti-rich phase will take place even for such basalts at the last stage of the small-scale differentiation. Characterization of their bulk chemistries in the TiO_2 *vs.* Mg/(Mg+Fe) diagram (KOEBERL *et al.*, 1993) indicates that these two rocks plot closer to the VLT field than to the low-Ti basalts despite their higher TiO_2 than the VLT.

As members of this consortium study, NISHIIZUMI *et al.* (1992) reported that the Moon-Earth transition times of Y-793169 (1.1 Ma) and A-881757 (0.9 Ma) are rather close, although the results do not suggest pairing. WARREN and KALLEMEYN (1992) found also that the bulk chemistries of the two samples are similar and particularly in both meteorites the heavy REE are enriched over La in comparison with other VLT mare basalts. Y-793169 and A-881757 also have higher bulk TiO_2 contents than the VLT basalts (WARREN and KALLEMEYN, 1992).

Our mineralogical data do not support pairing of Y-793169 and A-881757, but their crystallization trends are in line with a hypothesis that Y-793169 may have crystallized near the surface in disequilibrium growth condition, whereas A-881757 crystallized at depth under conditions closer to equilibrium condition in similar lava unit. The most Mg-rich pyroxene composition (mg-number = 50) found in A-881757 is still more Mg-rich than the bulk rock composition (mg-number = 35) (YANAI, 1991). This fact suggests that A-881757 still crystallized under fairly disequilibrium condition. If each was crystallized from the same lava, A-881757 should have been located deeper than Y-793169. They might have been ejected by the same impact from different depths, but reached Antarctica at slightly different times. Further studies are required to test this hypothesis.

5. Conclusions

(1) In spite of the proposed lunar origin of Y-793169, this basalt bears textural and mineralogical similarity to some eucrites; (2) Pyroxene chemical zoning trends of Y-793169 and A-881757 are distinct from eucrites and similar to those found in a rare basaltic clast in the Apollo 16 highland breccia, and the VLT basalts but are different from the trends of the low-Ti basalts of Apollo 12 and 15; (3) Ti/(Ti + Cr) *vs.* Fe/(Fe + Mg) plots of Y-793169 and A-881757 show a single trend with different starting points, but in between the low-Ti basalt trend of Apollo 15 and the VLTs; (4) The presence of fair amounts of ilmenite or ulvöspinel in mesostases of A-881757 and Y-793169 is consistent with their higher bulk TiO_2 contents as compared to the VLT basalts; (5) Assuming that Y-793169 and A-881757 were from a similar lava, A-881757 could represent growth condition closer approaching equilibrium than Y-793169, which might have been formed near the surface; (6) Mineralogy and the pyroxene chemical trends of Y-793169 and A-881757 are closer to those of the VLT than the low-Ti Apollo 12 and 15 basalts, but the term VLT may not be appropriate.

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