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Lherzolitic Martian meteorites Allan Hills 77005, Lewis Cliff 88516 and Yamato-793605: Major and minor element zoning in pyroxene and plagioclase glass

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Abstract: Three lherzolitic Martian meteorites (ALH77005, LEW88516 and Y-793605) show very similar petrography and mineralogy. They consist of the poikilitic and non-poikilitic (interstitial) areas that are heterogeneous on a cm-scale. A detailed electron microprobe analysis of pyroxene and plagioclase glass from these meteorites gives characteristic distributions of major and minor elements. It is striking that pyroxene and plagioclase glass in all three meteorites have nearly identical zoning patterns of these elements, while olivine shows different chemistry. This is because olivine chemistry was largely controlled by a late-stage re-equilibration which did not significantly modify the major and minor element distributions in pyroxene and plagioclase glass. However, a close look at minor element zoning in plagioclase glass exhibits slightly different zoning patterns among these three meteorites, corresponding to different degrees of re-equilibration (degrees of re-equilibration: ALH77005 > LEW88516 > Y-793605). Nevertheless, it is evident that they experienced a very similar igneous crystallization history and they are likely to have originated from the same igneous unit on Mars.

1. Introduction

Fourteen SNC (Shergottites-Nakhlites-Chassignite) meteorites are widely believed to have originated from the planet Mars (*e.g.*, McSween, 1985, 1994). They are very important samples since they provide an insight into igneous processes on Mars. The dominant group of Martian meteorites, shergottites, are divided into two subgroups consisting of basalts and lherzolites. The basaltic Martian meteorites include Shergotty, Zagami, Elephant Moraine A79001 (EETA79001), Queen Alexandra Range 94201 (QUE94201), Dar al Gani 476 and Dar al Gani 489 (although Dar al Gani 476 and Dar al Gani 489 are apparently paired (Folco *et al.*, 1999)). This subgroup mainly consists of pyroxene and plagioclase glass (usually called "maskelynite", see El Goresy *et al.* (1997)), but shows large textural variations from one specimen to another (*e.g.*, Mikouchi *et al.*, 1999). On the other hand, the lherzolitic group, all recovered from Antarctica (Allan Hills 77005 (ALH 77005), Lewis Cliff 88516 (LEW88516) and Yamato-793605 (Y-793605)), shows similar petrology and mineralogy within the group. The newest meteorite of this group is Y-793605 from the Japanese Antarctic meteorite collection. This meteorite has been extensively studied by the consortium investigation organized by National Institute of Polar Research (NIPR) (*e.g.,* Kojima *et al.*, 1997) and all the studies show close affinities of Y-793605 to ALH77005 and LEW88516 in petrography, mineralogy and isotope chemistry (Eugster and Polnau, 1997; Ikeda, 1997; Mikouchi and Miyamoto, 1997; Misawa *et al.*, 1997: Mittlefehldt *et al.*, 1997; Nagao *et al.*, 1997; Warren and Kallemeyn, 1997; Wadhwa *et al.*, 1999). This group is believed to have originated from the same igneous body on Mars.

Lherzolitic Martian meteorites are mainly composed of two different textures, poikilitic and non-poikilitic, with centimeter-scale heterogeneity (*e.g.,* Harvey *et al.*, 1993; Treiman *et al.*, 1994; Gleason *et al.*, 1997; Mikouchi and Miyamoto, 1997). Figure VIII-2 of Meyer (1998) shows a sawn surface of ALH77005, illustrating "light" and "dark" regions. The dark region corresponds to the non-poikilitic area and the light region corresponds to the poikilitic area. In the poikilitic area, a large pyroxene oikocryst encloses rounded olivine grains (reaching ~1 mm) and euhedral chromites (usually a few hundreds μm), and plagioclase glass is rarely observed. The non-poikilitic area is composed of nearly equal amounts of olivine, plagioclase glass and pyroxene. The sizes of olivine and plagioclase glass in the non-poikilitic area are larger than those in the poikilitic area. In both textures, pyroxenes and plagioclase glass are zoned in major and minor elements, providing us with useful information on their crystallization histories. Because olivine has faster Fe-Mg diffusion rates than pyroxene and plagioclase (*e.g.,* Jurewicz and Watson, 1988; Fujino *et al.*, 1990), olivines in three lherzolitic Marian meteorites show different degrees of homogenization of Fe-Mg zoning profiles. Olivines in LEW 88516 and Y-793605 preserve chemical zoning, while ALH77005 olivine is nearly homogenized, suggesting a higher degree of equilibration (*e.g.,* Harvey *et al.*, 1993; Treiman *et al.*, 1994; Ikeda, 1997; Mikouchi and Miyamoto, 1997; Wadhwa *et al.*, 1999). In this study we paid attention to chemical zoning of major and minor elements in pyroxene and plagioclase glass and discuss petrogenetic relationships and igneous crystallization histories of the lherzolitic Martian meteorites (Wadhwa *et al.*, 1999).

2. Samples and analytical techniques

Mineral analyses were made on polished thin sections of ALH77005 (ALH 77005,93-1) and Y-793605 (Y-793605,51-2) both supplied by NIPR and LEW88516 (LEW88516,24) supplied by the Meteorite Working Group (MWG) of NASA Johnson Space Center. Quantitative wavelength dispersive analyses were performed on a JEOL 733 electron microprobe (Ocean Research Institute, University of Tokyo) and a JEOL JCM 733 mk II microprobe (Geological Institute, University of Tokyo). Electron microprobes were operated at 15 kV accelerating voltage and beam current was 12 nA on a Faraday cage. The detection limits of minor elements in pyroxene and plagioclase are as follows. TiO_2 is 0.1 wt%. Al_2O_3 is 0.05 wt%. FeO is 0.1 wt%. MnO is 0.12 wt%. MgO is 0.05 wt%. CaO is 0.06 wt%. Na_2O is 0.08

wt%. K_2O is 0.06 wt%. Cr_2O_3 is 0.14 wt%. We employed a defocused beam of ~5 μm in diameter with the beam current of 8 nA to minimize loss of volatile elements during analysis of plagioclase glass.

3. Major and minor element zoning in pyroxene and plagioclase glass

Representative mineral compositions of pyroxene and plagioclase glass in three lherzolitic Martian meteorites are summarized in Tables 1–3.

3.1. *Pyroxene*

All three lherzolitic Martian meteorites are composed of poikilitic and non-poikilitic (interstitial) areas. They include pigeonite, olivine, augite, plagioclase glass, chromite and several other accessory minerals (Harvey *et al.*, 1993; Treiman *et al.*, 1994; Gleason *et al.*, 1997; Ikeda, 1997; Mikouchi and Miyamoto, 1997). ALH77005,93-1 (about 13×6 mm) is mainly composed of poikilitic areas that reach 6 mm in diameter (Fig. 1a). The non-poikilitic regions are present between the large oikocrystic pyroxenes as vein-like forms (~2 mm wide). On the other hand, the poikilitic area is observed only in a small part of LEW88516,24 (about 10 ×7 mm) unlike ALH77005 (Fig. 1b). Gleason *et al.* (1997) also reported minor portion of the poikilitic area comparing with the non-poikilitic area in their thin section. Y-793605,51-2 is about 9×6 mm in size and is principally poikilitic in texture (Fig. 1c). It contains a small portion of the non-poikilitic region. Large impact melt pockets that partially formed by skeletal recrystallizing olivines are observed in ALH77005 and LEW88516, while the thin section of Y-793605 studied does not contain such a melt pocket.

Oikocrystic pigeonites are systematically zoned in all three meteorites. The major element compositions are almost identical among three and range from $En_{77}Fs_{19}Wo_4$ to $En_{65}Fs_{20}Wo_{15}$ in ALH77005, from $En_{77}Fs_{20}Wo_3$ to $En_{65}Fs_{21}Wo_{14}$ in LEW88516 and from $En_{76}Fs_{21}Wo_3$ to $En_{66}Fs_{23}Wo_{11}$ in Y-793605 (Fig. 2). The observation of the lowest-Ca pyroxene by an optical microscope suggests a monoclinic crystal system. However, it is unclear whether this reflects any igneous processes or it is due to later shock events. Most augite grains in the poikilitic area are present as irregular bands of 0.5–1 mm wide rimming the oikocrysts. Small augite patches within the oikocrysts are observed in LEW88516 and Y-793605, but they are rare in ALH77005. The poikilitic augite compositions are nearly identical among three meteorites. They range from $En_{55}Fs_{15}Wo_{30}$ to $En_{48}Fs_{12}Wo_{40}$ in ALH 77005, from $En_{55}Fs_{16}Wo_{29}$ to $En_{48}Fs_{14}Wo_{38}$ in LEW88516, from $En_{52}Fs_{16}Wo_{32}$ to $En_{49}Fs_{14}Wo_{37}$ in Y-793605 (Fig. 2). The pyroxene equilibration temperature using a two-pyroxene thermometer (Lindsley and Andersen, 1983) is about 1150°C for the pigeonite-augite pair from the all three meteorites. This is consistent with the estimation by Ishii *et al.* (1979) and Mikouchi and Miyamoto (1997).

Pyroxenes in the non-poikilitic areas are much smaller (~0.5 mm) than those in the poikilitic area and they are subhedral to anhedral. Most pyroxene grains in the non-poikilitic area are pigeonite and augite is quite rare. Pigeonite in the

Table 1. Mineral composition of pyroxene and plagioclase glass in ALH77005.

	Poikilitic area					Non-poikilitic area				
	Pigeonite (core)	Pigeonite (rim)	Augite	Plagioclase glass (core)	Plagioclase glass (rim)	Pigeonite (core)	Pigeonite (rim)	Augite	Plagioclase glass (core)	Plagioclase glass (rim)
SiO_2	55.83	54.70	52.00	55.71	55.75	54.60	53.82	53.55	55.58	58.57
Al_2O_3	0.33	0.80	1.90	27.21	27.57	0.90	1.29	1.57	27.52	26.00
TiO_2	0.09	0.20	0.50	0.09	0.15	0.52	0.66	0.40	0.08	0.22
FeO	13.00	14.40	8.90	0.35	0.51	16.68	15.42	7.93	0.42	0.50
MnO	0.46	0.50	0.40	-	0.03	0.60	0.57	0.33	0.07	0.04
MgO	28.20	23.60	16.70	0.26	0.28	23.27	21.11	17.24	0.22	0.21
CaO	1.63	5.60	17.60	10.67	10.02	3.84	7.19	18.09	10.81	8.61
Na_2O	0.02	-	0.20	4.57	5.33	0.05	0.06	0.09	4.43	4.72
K_2O	0.01	-	-	0.07	0.45	-	0.01	-	0.22	0.36
Cr_2O_3	0.44	0.50	0.80	0.02	0.01	0.37	0.40	0.97	-	0.01
V_2O_3	0.05	-	0.10	0.03	-	-	0.08	0.10	0.04	-
NiO	0.07	-	0.10	0.03	-	-	-	-	-	-
P_2O_5	0.00	0.40	0.10	-	-	0.01	-	-	0.19	0.06
Total	100.13	100.70	99.30	99.01	100.11	100.83	100.60	100.25	99.59	99.29
Fs	*19.9*	*22.6*	*14.4*			*26.4*	*24.8*	*12.8*		
En	*76.9*	*66.2*	*48.7*			*65.8*	*60.4*	*49.7*		
Wo	*3.2*	*11.2*	*36.9*			*7.8*	*14.8*	*37.5*		
An				*56.1*	*49.6*				*56.6*	*49.0*
Ab				*43.5*	*47.7*				*42.0*	*48.6*
Or				*0.5*	*2.7*				*1.3*	*2.4*

Table 2. Mineral composition of pyroxene and plagioclase glass in LEW88516.

	Poikilitic area					Non-poikilitic area				
	Pigeonite (core)	Pigeonite (rim)	Augite	Plagioclase glass (core)	Plagioclase glass (rim)	Pigeonite (core)	Pigeonite (rim)	Augite	Plagioclase glass (core)	Plagioclase glass (rim)
SiO_2	55.18	54.32	53.03	55.53	55.83	54.49	53.33	52.56	55.56	57.89
Al_2O_3	0.39	0.64	1.32	28.36	27.46	0.53	0.95	1.82	27.48	26.38
TiO_2	0.10	0.13	0.27	0.07	0.13	0.10	0.20	0.33	0.08	0.15
FeO	13.46	13.91	8.79	0.40	0.43	15.32	14.57	9.24	0.36	0.32
MnO	0.45	0.57	0.38	-	-	0.56	0.55	0.37	-	0.03
MgO	28.02	24.14	17.58	0.13	0.12	24.99	22.81	16.74	0.13	0.08
CaO	1.91	6.14	16.96	11.12	10.68	3.54	6.53	17.55	10.86	9.34
Na_2O	0.04	0.08	0.20	3.97	4.56	0.05	0.09	0.21	4.79	5.54
K_2O	-	-	0.02	0.17	0.22	-	-	-	0.16	0.35
Cr_2O_3	0.42	0.41	0.84	-	0.05	0.39	0.53	0.86	0.01	0.03
V_2O_3	0.04	-	0.04	0.04	0.02	0.06	-	0.07	-	0.01
NiO	-	0.05	-	-	0.01	0.01	0.04	0.03	-	-
P_2O_5	-	0.16	0.40	-	-	0.05	0.13	0.19	-	-
Total	100.02	100.53	99.84	99.60	99.49	100.07	99.72	99.98	99.41	100.10
Fs	*20.4*	*21.5*	*14.2*			*23.8*	*22.9*	*15.0*		
En	*75.8*	*66.4*	*50.7*			*69.2*	*63.9*	*48.5*		
Wo	*3.7*	*12.1*	*35.1*			*7.0*	*13.2*	*36.5*		
An				*60.0*	*55.7*				*55.1*	*47.2*
Ab				*38.8*	*43.0*				*44.0*	*50.7*
Or				*1.1*	*1.3*				*0.9*	*2.1*

Table 3. Mineral composition of pyroxene and plagioclase glass in Y-793605.

	Poikilitic area					Non-poikilitic area				
	Pigeonite (core)	Pigeonite (rim)	Augite	Plagioclase glass (core)	Plagioclase glass (rim)	Pigeonite (core)	Pigeonite (rim)	Augite	Plagioclase glass (core)	Plagioclase glass (rim)
SiO_2	56.01	54.71	51.99	55.51	59.79	54.01	53.19	52.21	54.91	57.21
Al_2O_3	0.30	0.80	1.90	27.90	25.50	0.60	1.10	1.70	27.60	26.50
TiO_2	0.10	0.20	0.50	0.10	0.20	0.70	0.60	0.80	0.10	0.20
FeO	13.40	14.40	8.90	0.51	0.41	17.00	14.90	10.00	0.50	0.40
MnO	0.40	0.50	0.40	-	-	0.80	0.50	0.40	-	-
MgO	28.00	23.60	16.70	0.20	0.10	22.90	21.30	16.40	0.20	0.10
CaO	1.40	5.60	17.60	10.90	8.20	3.70	7.10	17.10	11.10	9.70
Na_2O	-	-	0.21	4.50	4.90	0.10	0.10	0.30	4.40	5.00
K_2O	-	-	-	0.30	0.40	-	-	-	0.30	0.30
Cr_2O_3	0.40	0.51	0.79	-	-	0.20	0.50	0.80	-	0.10
V_2O_3	-	-	0.08	-	-	-	-	0.10	-	-
NiO	-	-	0.09	-	-	-	-	-	-	-
P_2O_5	0.09	0.38	0.08	0.08	0.10	-	-	0.19	0.19	0.09
Total	100.10	100.70	99.24	100.00	99.60	100.01	99.29	100.00	99.30	99.60
Fs	*20.5*	*22.6*	*14.4*			*27.2*	*22.6*	*16.4*		
En	*76.6*	*66.2*	*48.7*			*65.2*	*66.2*	*47.8*		
Wo	*2.8*	*11.2*	*36.9*			*7.6*	*11.2*	*35.8*		
An				*56.4*	*46.8*				*56.9*	*50.6*
Ab				*42.1*	*50.7*				*41.5*	*47.3*
Or				*0.5*	*2.5*				*1.6*	*2.1*

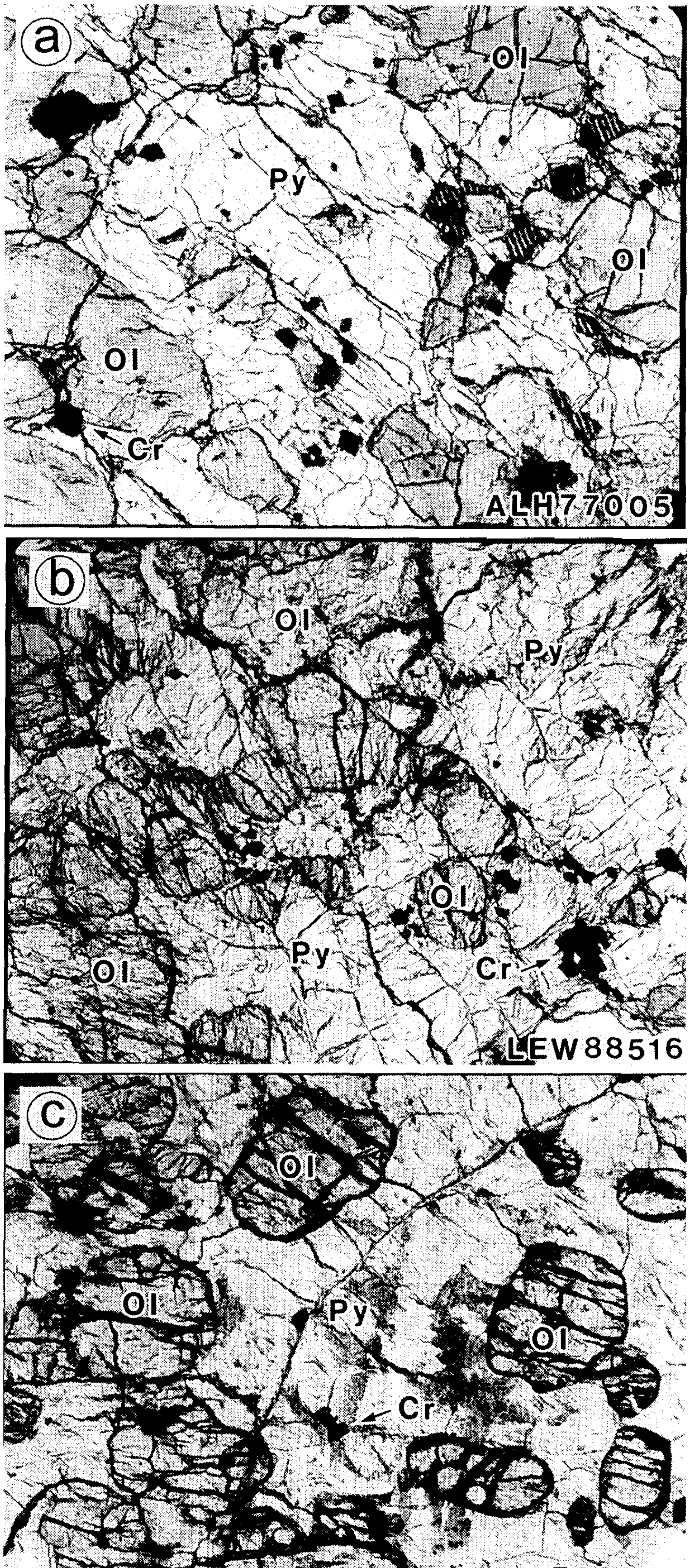

Fig. 1. Photomicrographs of the lherzolitic Martian meteorites (transmitted light). (a) ALH 77005, (b) LEW88516 and (c) Y-793605. The field of view is abont 2.2 mm in all photos. The fields show typical poikilitic areas showing large pyroxene oikocrysts enclosing rounded olivines and euhedral chromites. Ol: olivine. Py: pyroxene. Cr: chromite.

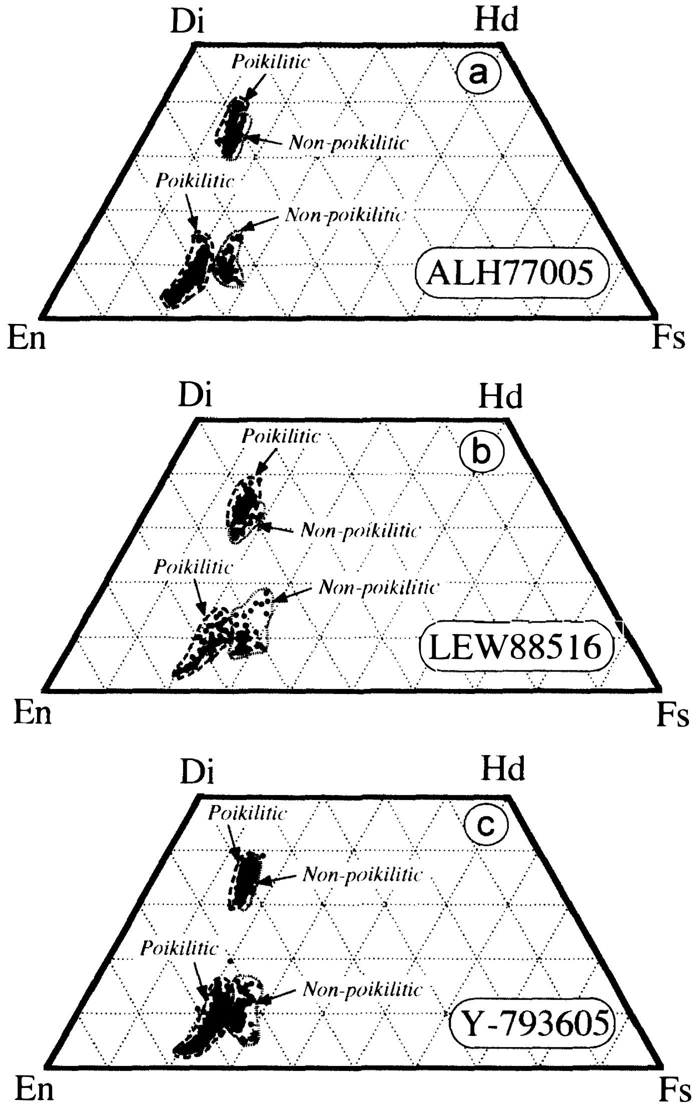

Fig. 2. Pyroxene quadrilaterals showing pyroxene compositions of (a) ALH77005, (b) LEW88516 and (c) Y-793605. The plotted data are from several pyroxene grains including both cores and rims. Each pyroxene grain shows a compositional variation that is almost similar from one grain to another. Low-Ca pyroxenes clearly have two clusters. Pigeonites in the non-poikilitic area are more Ca- and Fe-rich than those in the poikilitic area. The lowest Ca pyroxenes show coherent chemical zoning trends toward the Ca- and Fe-rich pigeonites. En: enstatite. Fs: ferrosilite. Di: diopside. Hd: hedenbergite.

non-poikilitic area is more Ca- and Fe-rich than that in the poikilitic area and the composition is scattered in both Ca and Fe contents (Fig. 2). The compositions range from $En_{66}Fs_{27}Wo_{7}$ to $En_{61}Fs_{23}Wo_{16}$ in ALH77005, from $En_{65}Fs_{28}Wo_{7}$ to $En_{54}Fs_{28}Wo_{18}$ in LEW88516 and from $En_{65}Fs_{28}Wo_{7}$ to $En_{60}Fs_{27}Wo_{13}$ in Y-793605 (Fig. 2). Unlike the poikilitic pigeonite, non-poikilitic pigeonite shows slightly different compositional distributions among three meteorites. This is probably because each non-poikilitic area became isolated from each other towards the end of the crystallization history of these rocks and evolved independently of each other as pointed out by Wadhwa *et al.* (1994). Augite compositions in the non-poikilitic areas are indistinguishable from those in the poikilitic areas. They range from $En_{53}Fs_{15}Wo_{32}$ to $En_{48}Fs_{14}Wo_{38}$ in ALH77005, from $En_{52}Fs_{17}Wo_{31}$ to $En_{47}Fs_{16}Wo_{37}$ in LEW88516 and in from $En_{65}Fs_{28}Wo_{7}$ to $En_{60}Fs_{27}Wo_{13}$ Y-793605 (Fig. 2).

Oikocrystic pigeonites show systematic increase in Al and Ti compositions, while pigeonite in the non-poikilitic area is more Ti-rich and shows a rather scattered distribution (Fig. 3). This is observed for all three meteorites. The Al_2O_3

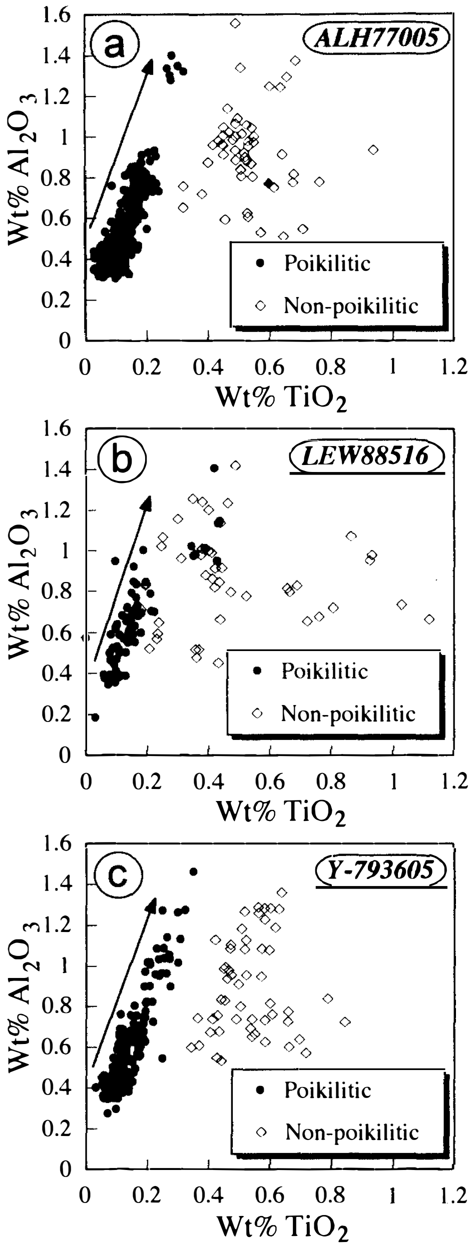

Fig. 3. Al and Ti distributions in low-Ca pyroxenes from (a) ALH77005, (b) LEW88516 and (c) Y-793605. The plotted data are from several pyroxene grains including both cores and rims. Each pyroxene grain shows a compositional variation that is almost similar from one grain to another. The low-Ca pyroxenes in the poikilitic area show a systematic zoning trend toward the Al- and Ti-rich compositions (arrows), whereas those in the non-poikilitic area are clearly more Ti-rich and have scattered compositions. The errors of each abundance are Al_2O_3: 0.05 wt% and TiO_2: 0.1 wt%.

concentrations increase from 0.3 wt% to 1.4 wt%. Similarly, the TiO_2 concentrations increase from 0.05 wt% to 0.3 wt%. There is a compositional cluster near Al_2O_3: 1 wt% and TiO_2: 0.5 wt% in the non-poikilitic pigeonite of ALH77005. The non-poikilitic pigeonite in LEW88516 extends to more Ti-rich compositions than that of ALH77005. This Ti-rich pigeonite corresponds to Ca- and Fe-rich pyroxene ($En_{55}Fs_{28}Wo_{17}$) seen in Fig. 2b. These abundances are in agreement with those of previous workers (*e.g.*, Harvey *et al.*, 1993; Treiman *et al.*, 1994; Wadhwa *et al.*, 1994; Ikeda, 1997; Mikouchi and Miyamoto, 1997; Wadhwa *et al.*, 1999).

3.2. *Plagioclase glass*

Although plagioclase glass is uncommon in the poikilitic area, they comprise a much larger proportion in the non-poikilitic area. Plagioclase glass in both areas has chemical zoning with almost identical composition in major elements. Major element compositions of plagioclase glass range from $An_{58}Ab_{41}Or_1$ to $An_{48}Ab_{49}Or_3$ in ALH77005, from $An_{58}Ab_{41}Or_1$ to $An_{48}Ab_{49}Or_3$ in LEW88516 and $An_{55}Ab_{44}Or_1$ at the center and $An_{45}Ab_{52}Or_3$ in Y-793605. Thus, plagioclase compositions are almost indistinguishable among three meteorites. Although Ikeda (1994) reported crystalline plagioclase rim with reverse major element zoning in ALH77005, we analyzed euhedral-shaped grains without these rims. The FeO and MgO contents in the non-poikilitic plagioclase glass show unique chemical zoning patterns (Fig. 4). Generally, FeO drops from 0.4–0.5 to 0.2–0.3 wt% in the core, and then it shows a little increase to 0.4–0.5 wt% toward the edge. Because MgO has a very low concentration in plagioclase, it does not exhibit clear zoning patterns. However,

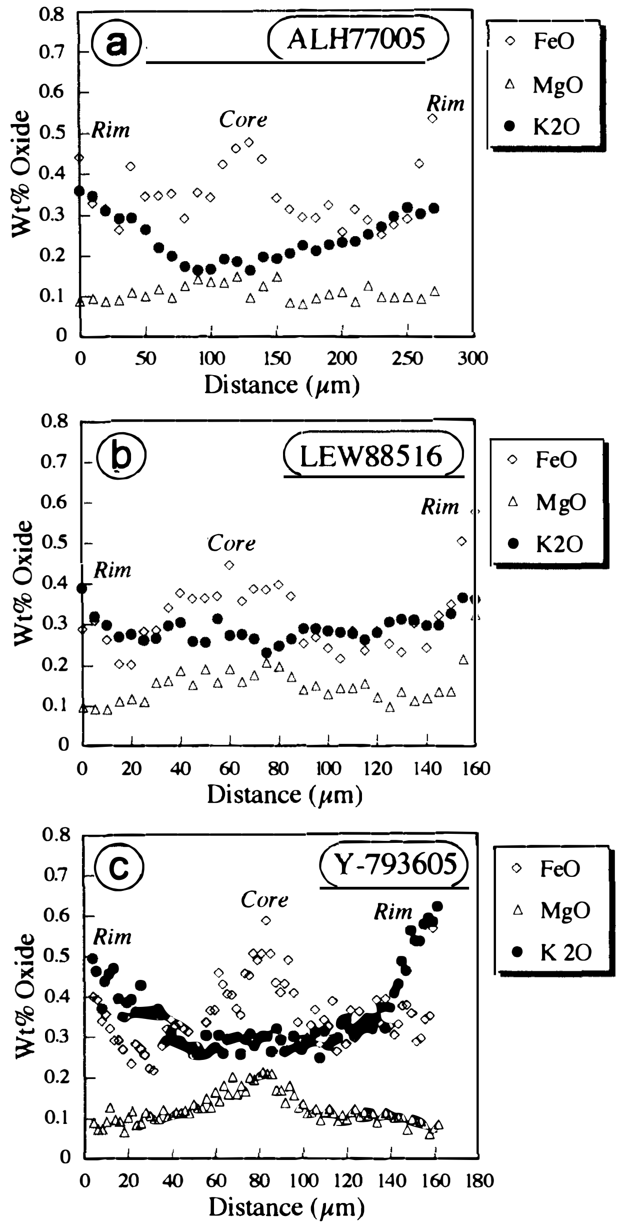

Fig. 4. FeO, MgO and K_2O zoning profiles of plagioclase glass from (a) ALH77005, (b) LEW88516 and (c) Y-793605. Note that Fe shows first decrease at the core regions, and then it again increases at the rims. Mg is correlated with Fe in Y-793605 although it is nearly homogeneous in ALH77005. The errors of each abundance are FeO: 0.1 wt%, MgO 0.05 wt% and K_2O: 0.06 wt%.

MgO decreases from 0.2 to 0.1 wt% as Fe decreases in Y-793605. MgO is nearly constant in ALH77005. K_2O shows increase from core to rim and does not seem to show any particular relations with Fe and Mg. Plagioclase glass in the poikilitic area usually does not show systematic zoning in minor elements from core to rim due to the irregular shape of the grain.

4. Constraints on the crystallization histories of lherzolitic Martian meteorites

It should be noted that major and minor elements in pyroxene and plagioclase glass from these three lherzolitic Martian meteorites show very similar zoning patterns to one another. Similar observation has been reported for trace elements in these phases by Wadhwa *et al.* (1999). Thus, this study further supports an idea that these three meteorites have a very close petrogenetic relationship (*e.g.*, Ikeda, 1997; Mikouchi and Miyamoto, 1997; Warren and Kallemeyh, 1997; Wadhwa *et al.*, 1999). The cosmic ray exposure ages of three meteorites are consistent with this conclusion (Eugster and Polnau, 1997; Nagao *et al.*, 1997).

Minor element behavior in pigeonite and plagioclase glass can be a key to understanding the formation histories of lherzolitic Martian meteorites. Harvey *et al.* (1993), Ikeda (1997), Mikouchi and Miyamoto (1997) and Wadhwa *et al.* (1999) proposed crystallization models of these three lherzolitic Martian meteorites. This study generally supports their models as follows. Crystallization of cumulus phases (olivine and chromite) occurred at first. After crystallization of cumulus phases, oikocrystic pigeonites were formed as products of progressive fractional crystallization. Then, crystallization progressed to the pigeonite-augite cotectic, where pigeonite and augite co-crystallized. The liquid composition reached the eutectic, where minor amount of plagioclase began to crystallize. In the non-poikilitic area, we expect that each melt pocket had a different melt composition from one another (*e.g.*, Wadhwa *et al.*, 1994). However, they might be generally similar, and pigeonite and plagioclase co-crystallized at the first stages. Decrease of Fe and Mg concentrations in the core of plagioclase glass suggests that plagioclase co-crystallized with an Fe- and Mg-bearing phase(s) (Fig. 4). This is consistent with the observation that the non-poikilitic area contains an intergrowth texture of pigeonite and plagioclase (*e.g.*, Fig. 2a of Mikouchi and Miyamoto, 1997). Such a texture is typically observed in some basaltic Martian meteorites (*e.g.*, Stolper and McSween, 1979; McCoy *et al.*, 1992; McSween, 1994; Mikouchi *et al.*, 1999). The Fe content in plagioclase might decrease as crystallization of these phases continues, because pyroxenes took much Fe in the melt, resulting in Fe decrease in the plagioclase cores. However, Fe then increases at the rim portion of plagioclase as Fig. 4 shows. In order to explain this, one possibility is a change of geological setting (*e.g.*, change of temperature, pressure). If this kind of event has happened, it could bring about a shift of the phase boundaries. McCoy *et al.* (1992) employed an idea of this kind of phase boundary shifts to explain crystallization sequences of the Zagami Martian meteorite based on several independent facts. However, in the case of these three lherzolitic Martian meteorites, plagioclase rims in the non-poikilitic regions were formed towards the very last stages of this crystallization sequences. Therefore, it is unlikely to consider that highly crystallized melt migrated to cause a phase boundary shift. The other possibility is that Fe contents at the plagioclase rims were modified by secondary re-equilibration. It is evident that these three lherzolites experienced minor degrees of re-equilibration at the last stages of their formation histories (*e.g.*, Harvey *et al.*, 1993; Mikouchi and Miyamoto, 1997). Olivine in ALH77005 shows a tight compositional distribution around Fa_{24-30} and no compositional difference is seen between the poikilitic and non-poikilitic areas. On the other hand, olivines in LEW88516 and Y-793605 preserve chemical zoning in each grain of the poikilitic area. Especially, olivine grains located near the center of the pyroxene oikocrysts have the most magnesian compositions and have the most extensive chemical zoning (*e.g.*, Harvey *et al.*, 1993). Olivine in LEW88516 ranges from Fa_{26} to Fa_{38} and that in Y-793605 is from Fa_{26} to Fa_{36}. In each meteorite, olivines in the non-poikilitic area have more ferroan and homogeneous compositions than those in the poikilitic area (*e.g.*, Harvey *et al.*, 1993; Ikeda, 1997; Mikouchi and Miyamoto, 1997). This olivine chemistry is understood by the hypothesis that ALH77005 experienced more intense re-equilibration than LEW88516 and Y-793605, causing homogenization of ALH 77005 olivine (*e.g.*, Harvey *et al.*, 1993; Mikouchi and Miyamoto, 1997; Wadhwa *et al.*, 1999). The preservation of major and minor element zoning in pyroxene and plagioclase glass even observed in ALH77005 is probably achieved by slower Fe and Mg diffusion rates in pyroxene and plagioclase compared to olivine (*e.g.*, Jurewicz and Watson, 1988; Fujino *et al.*, 1990). Minor element zoning in ALH77005 plagioclase looks smoother than that in Y-793605 and that of LEW88516 is intermediate between the two (Fig. 4). Although Fe and Mg diffusion rates in plagioclase are unknown, we suggest that they be faster than those of pyroxene are, but slower than those of olivine. Harvey *et al.* (1993) and Treiman *et al.* (1994) explained that augite bands in the pyroxene oikocrysts are exsolution products during re-equilibration. However, we believe that augite is a product of igneous crystallization because growth of such thick augite lamellae ($\sim$1 mm) could undoubtedly erase chemical zoning of olivine, which is preserved in LEW88516 and Y-793605.

In spite of these minor differences among these three lherzolitic Martian meteorites, it is evident that they experienced a very similar igneous crystallization history and they are likely to have originated from the same igneous unit on Mars as suggested by Warren and Kallemeyh (1997) and Wadhwa *et al.* (1999).

5. Summary

Major and minor element characteristics in pyroxene and plagioclase glass of three lherzolitic Martian meteorites (ALH77005, LEW88516 and Y-793605) show remarkable affinities to one another. It is likely that these three meteorites shared a common petrogenesis on Mars and formed in the same igneous body as many previous studies proposed (*e.g.*, Mikouchi and Miyamoto, 1997; Warren and

Kallemeyh, 1997; Wadhwa *et al.*, 1999). The same cosmic-ray exposure age of three meteorites also indicates that they were ejected from Mars by the same impact event (Eugster and Polnau, 1997; Nagao *et al.*, 1997) and reached different areas in Antarctica as different falls (Nishiizumi and Caffee, 1997). Such a relationship of three lherzolitic Martian meteorites is similar to that observed in three nakhlites (Nakhla, Lafayette, and Governador Valadares) as pointed out by Wadhwa *et al.* (1999). Olivine shows different mineral compositions among three meteorites. This is due to different degrees of later re-equilibration events (ALH77005 olivine is nearly homogeneous: highest degree of re-equilibration. Y-793605 olivines preserve chemical zoning: lowest degree of re-equilibration. LEW88516 is intermediate between the two). Minor element characteristics in plagioclase also appear to reflect these different degrees of re-equilibration, suggesting that Fe and Mg diffusion rate in plagioclase is intermediate between those of pyroxene and olivine.

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