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Mineralogical similarities and differences between the Los Angeles basaltic shergottite and the Asuka-881757 lunar mare meteorite

Takashi Mikouchi[1,2]

[1] *Department of Earth and Planetary Science, Graduate School of Science, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-0033*
[2] *Mail Code SN2, NASA Johnson Space Center, Houston, TX 77058, U.S.A.*

Abstract: Los Angeles, a new basaltic shergottite, is a coarse-grained rock composed of pyroxene and plagioclase ("maskelynite") plus abundant late-crystallization phases. Pyroxenes are Fe-rich and show extensive chemical zoning from pigeonite and augite individual cores to Fe-rich pigeonite rims. The chemical zoning of plagioclase, though it is only slightly zoned, suggests that it grew outward from the most calcic part near the pyroxene walls. One of the most remarkable characteristics of Los Angeles is the presence of complex mixtures of hedenbergite + fayalite + silica, presumably breakdown products of pyroxferroite. Among the previously known basaltic shergottites, QUE94201 shows similar mineralogy to Los Angeles (the melt pockets in Zagami is also similar to Los Angeles). However, Los Angeles is clearly different from QUE94201 in several mineralogical respects, and they do not appear geochemically related. In spite of the origin from the different parent body, the Asuka-881757 lunar mare meteorite shows remarkable similarities to Los Angeles. Asuka-881757 is composed of large Fe-rich pyroxene and plagioclase grains with abundant hedenbergite + fayalite + silica mixtures. The pyroxene zoning and exsolution features of Asuka-881757 are similar to those of Los Angeles rather than QUE 94201. It is likely that Los Angeles and Asuka-881757 experienced similar crystallization and cooling histories although they came from different planetary bodies, Mars and the Moon, respectively.

1. Introduction

Los Angeles is a new basaltic shergottite that was found in October, 1999 in a private rock collection of an amateur rock collector in California, USA (Rubin *et al.*, 2000a). The Los Angeles meteorite comprises of two individual stones weighing 452.6 g and 245.4 g, respectively (Rubin *et al.*, 2000a,b). Los Angeles is a coarse-grained basalt mainly composed of plagioclase (shock transformed to "maskelynite") and pyroxene with abundant late-stage crystallization phases and shock melt pockets. The average mineral sizes of pyroxene and plagioclase in Los Angeles reach 1 mm, which exceed those of most other basaltic shergottites (*e.g.*, Mikouchi *et al.*, 1999) (although QUE94201 shows a similar coarse-grained texture). General petrography and mineralogy of Los Angeles most resemble those of QUE94201 among previously known basaltic shergottites, yet these two meteorites are clearly distinct as described in the following chapters. Zagami also contains a coarse-grained lithology of late-stage crystallization melt pockets similar to Los Angeles (McCoy *et al.*, 1999). Because discovery of new

Martian meteorites can bring about new insights into understanding crystallization of Martian magmas and their source regions, Los Angeles is also expected to offer such useful information. Furthermore, QUE94201 shows several affinities to lunar mare basalts in mineralogy and chemistry (McSween *et al.*, 1996; Mikouchi *et al.*, 1996, 1998; Wadhwa *et al.*, 1998). The similarity between the two basalts mostly appears attributed to continuous, closed system fractional crystallization at relatively reducing fO_2 conditions (Wadhwa *et al.*, 1998). In my preliminary report (Mikouchi, 2000), I suggested that Los Angeles also shows similar mineralogy to some lunar mare basalts. In this paper, I further analyzed Los Angeles and lunar mare meteorites as well as other basaltic shergottites in order to elucidate similarities and differences in their origin between these two meteorite groups from different planetary bodies, Mars and the Moon.

2. Samples and analytical techniques

Mineral analyses were mainly performed on polished thin sections of Los Angeles (Los Angeles from UCLA) basaltic shergottite and Asuka-881757 (A-881757,53E-2 from NIPR) lunar mare meteorite. QUE94201 (QUE94201,34 from the Meteorite Working Group) basaltic shergottite and Yamato-793169 (Y-793169,51-3 from NIPR) lunar mare meteorite were also analyzed for comparison. Backscattered electron (BSE) images were taken with JEOL JXA840 and Hitachi S-4500 scanning electron microscopes with energy dispersive spectrometers (EDS) (Dept. Earth Planet. Sci., University of Tokyo). The Hitachi SEM has a field emission gun and is used to obtain high magnification BSE images. Elemental distribution maps were acquired by a JEOL JXA 8900L electron microprobe (Dept. Earth Planet. Sci., University of Tokyo). Accelerating voltage was 15 kV, and the beam current was 120 nA. Modal abundances of minerals were calculated by combination of Mg (pyroxene), Fe (fayalite), Ca (Ca phosphates), Al (plagioclase), Ti (ulvöspinel + ilmenite), Si (silica), Na (plagioclase), and K (K-rich feldspathic glass) maps of the 7.2 × 4.8 mm area. Quantitative wavelength dispersive analyses were performed on a JEOL Superprobe 733 electron microprobe (Ocean Research Institute, University of Tokyo) and a JEOL JCM 733 mk II microprobe (Dept. Earth Planet. Sci., University of Tokyo) by using natural and synthetic standards. Microprobe analyses of most phases were obtained at 15 kV accelerating voltage with a beam current of 12 nA. Very gentle condition was employed for plagioclase analysis (defocused beam of 10 μm in diameter and probe current of 8 nA) to minimize volatile loss during analysis of plagioclase (Mikouchi *et al.*, 1999).

3. Petrology and mineralogy of Los Angeles

Los Angeles shows a coarse-grained basaltic texture composed of nearly subequal amounts of plagioclase and pyroxene with abundant late-crystallization phases (K-rich feldspathic glass, silica, merrillite, apatite, fayalite, ulvöspinel, and pyrrhotite) plus shock melt pockets (Fig. 1). The thin section studied (*ca.* 15 × 5 mm) gives the following modal abundances of minerals by combination of several elemental distribution maps: 45.0% plagioclase, 41.6% pyroxenes, 3.7% K-rich feldspathic glass, 2.7%

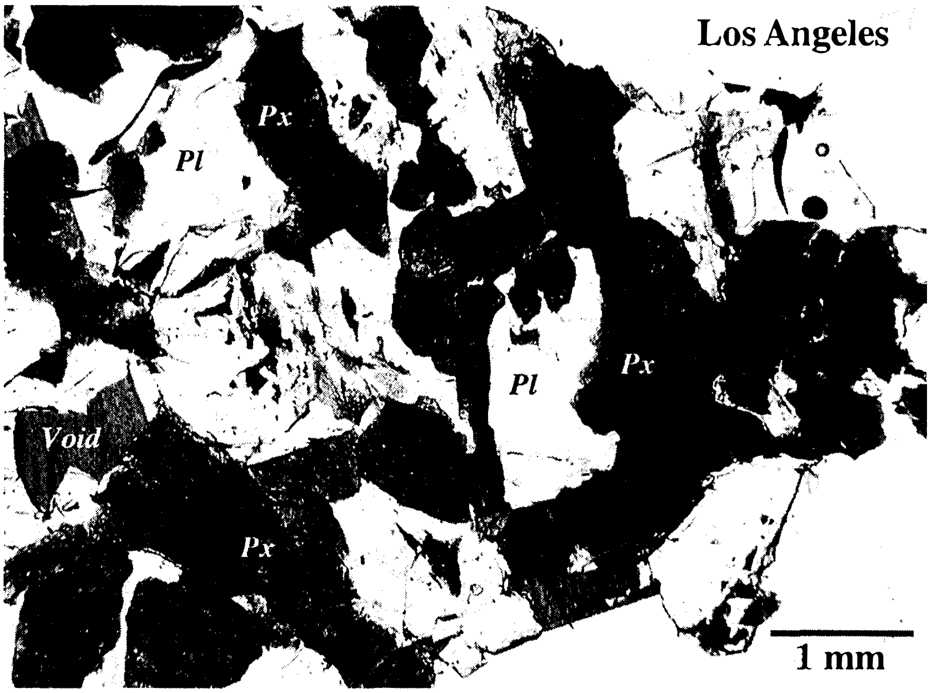


Fig. 1. Photomicrograph of Los Angeles. The scale bar is 1 mm. Pyroxenes (Px) show dark appearance, probably due to shock. Plagioclases (Pl) are transformed into amorphous states ("maskelynites").

silica, 2.3% Ca phosphates (merrillite+apatite), 1.9% fayalite, 1.7% ulvöspinel (+ minor ilmenite) and 1.1% others, in accordance with those by Rubin *et al.* (2000a). It is remarkable that Los Angeles contains abundant fine-grained wormy mixture of hedenbergite, fayalite, and silica. Representative mineral compositions of major phases in Los Angeles are summarized in Table 1.

3.1. *Pyroxene*

Pyroxenes in Los Angeles are present as low-Ca pyroxene (pigeonite) and high-Ca pyroxene (augite). They are typically euhedral to subhedral, reaching up to 3 mm long. Undulatory or mosaic extinction is common for pyroxenes, indicating strong shock effects. Pyroxene compositions are very Fe-rich and they show extensive chemical zoning towards nearly Mg-free compositions. Pigeonite and augite in Los Angeles are present as large blocky grains. Typically, the magnesian cores of pigeonite ($Wo_{10}En_{50}Fs_{40}$) and augite ($Wo_{33}En_{40}Fs_{27}$) are rimmed by Fe-rich pigeonite ($Wo_{15}En_5Fs_{80}$) (Figs. 2a, 2b). The Ca zoning pattern is especially irregular showing complex mixtures of Ca-rich and Ca-poor areas (Fig. 2a). Both pigeonite and augite contain fine exsolution lamellae of each other. The lamella widths are usually about 0.5μm, but in some areas it reaches a few μm (Fig. 2a). Some of the lamellae are faulted, probably due to shock effects.

The Al_2O_3 content of Los Angeles pigeonites ($Wo_{<20}$) drops from 1.2 wt% to 0.5 wt% as *fe#* (Atomic Fe/(Fe+Mg)) increases although the cores show compositional variation (0.5–1.2 wt%) at the constant *fe#* of 0.42–0.45, presumably due to the presence of fine exsolution lamellae. Augite shows a decrease of Al_2O_3 (1.3–0.7 wt%)

Table 1. Representative mineral compositions of major phases in Los Angeles basaltic shergottite.

	Pigeonite (Core)	Augite (Core)	Pigeonite (Rim)	Plagioclase (An-rich)	Plagioclase (An-poor)	K-rich feld-spathic glass	Merrillite	Apatite	Ulvöspinel	Silica	Fayalite	Hedenbergite	Shock melt
SiO_2	51.35	52.00	47.33	55.87	59.49	74.67	0.10	0.74	0.04	97.34	30.63	47.82	42.33
Al_2O_3	0.80	1.43	0.51	27.56	24.86	13.24	0.01	0.00	1.67	1.84	0.01	0.59	3.38
TiO_2	0.19	0.33	0.49	0.03	0.01	0.21	0.02	0.04	24.52	0.17	0.27	0.92	1.21
FeO	23.44	14.91	39.30	0.47	0.55	0.35	4.69	0.81	69.24	0.00	62.42	29.76	29.38
MnO	0.73	0.61	0.87	0.01	0.04	0.06	0.19	0.12	0.55	0.00	1.05	0.91	0.72
MgO	17.51	13.35	2.23	0.13	0.03	0.01	0.75	0.00	0.13	0.00	2.94	1.92	0.94
CaO	5.75	16.61	8.21	10.74	8.14	0.54	44.16	51.78	0.07	0.14	0.25	17.19	11.57
Na_2O	0.08	0.15	0.08	4.48	5.17	2.47	0.67	0.00	0.00	0.42	0.04	0.14	0.27
K_2O	0.03	0.02	0.01	0.17	0.69	5.33	0.04	0.03	0.01	0.02	0.02	0.01	0.49
Cr_2O_3	0.07	0.12	0.00	0.00	0.02	0.00	0.00	0.07	0.03	0.02	0.01	0.00	0.01
V_2O_3	0.09	0.09	0.02	0.00	0.03	0.06	0.03	0.04	0.35	0.00	0.01	0.00	0.05
NiO	0.02	0.00	0.05	0.00	0.00	0.01	0.00	0.00	0.01	0.00	0.06	0.00	0.01
P_2O_5	0.10	0.00	0.10	0.07	0.08	0.07	45.59	42.45	0.00	0.00	0.07	0.16	6.51
Total	100.16	99.61	99.19	99.52	99.10	97.01	96.25	96.08	96.60	99.94	97.78	99.43	96.88
Fs	*37.8*	*24.9*	*73.1*									*53.9*	
En	*50.3*	*39.7*	*7.4*									*6.2*	
Wo	*11.9*	*35.5*	*19.5*									*39.9*	
An				*56.4*	*44.4*								
Ab				*42.6*	*51.1*								
Or				*1.1*	*4.5*								

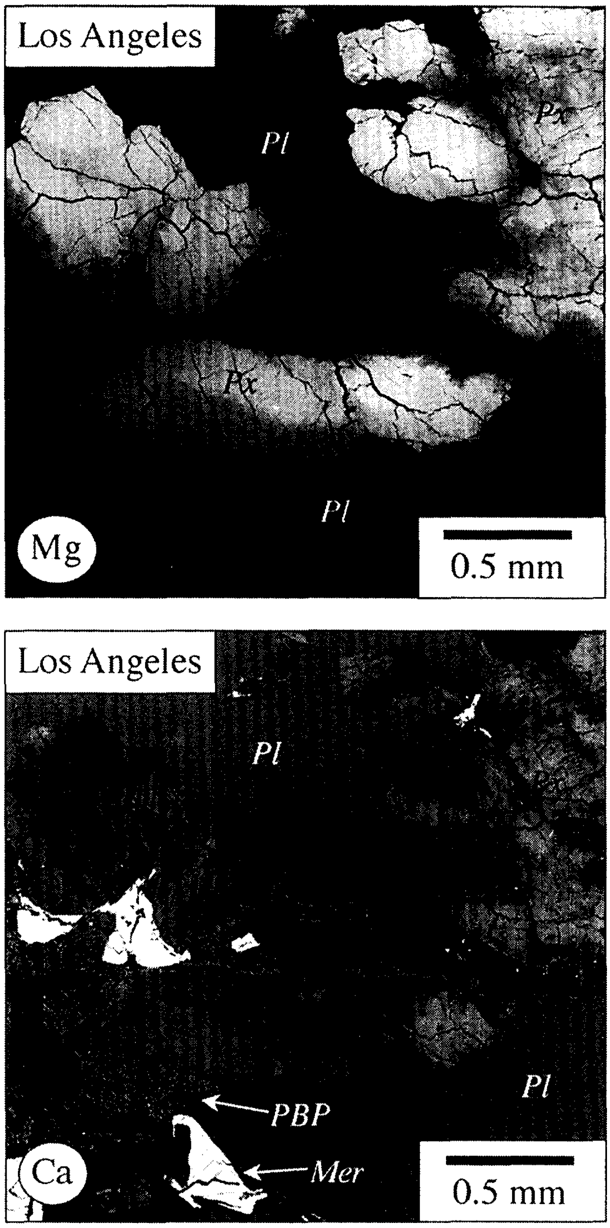


Fig. 2 (a). Mg and Ca X-ray Kα distribution maps of Los Angeles. The scale bars are 0.5 mm. Pyroxenes show very complicated chemical zoning from Mg-rich cores (both pigeonite and augite) to Fe-rich rims. Some areas show exsolution features. Px: pyroxene. Pl: plagioclase. Mer: merrillite. PBP: pyroxferroite breakdown products.

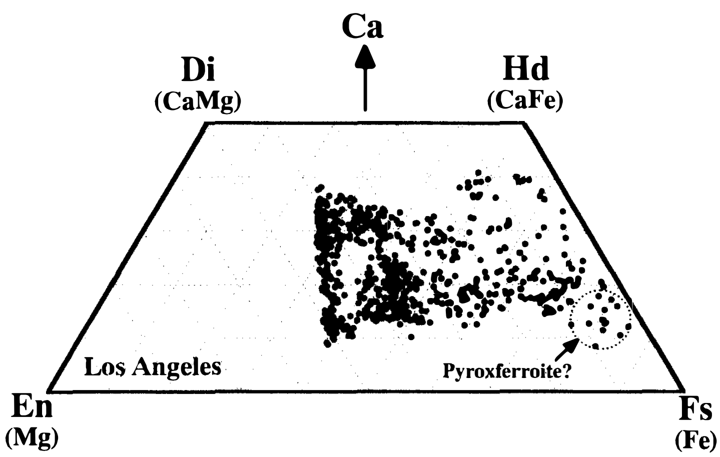


Fig. 2 (b). Pyroxene quadrilateral of Los Angeles. The compositions extend to very Fe-rich regions. Low-Ca and Fe-rich compositions may correspond to pyroxferroite.

with increasing *fe#*. TiO_2 in pigeonite increases from cores (0.15–0.3 wt%) to rims (0.5–0.6 wt%) although the extremely Fe-rich rims (*fe#* >0.9) (pyroxferroite?) have lower TiO_2 of 0.2–0.4 wt%. Augite shows an increase of TiO_2 from 0.3 wt% to 0.6 wt%. Los Angeles pyroxenes contain ~ 0.15 wt% Cr_2O_3 and V_2O_3.

3.2. Plagioclase

Plagioclase in Los Angeles, usually subhedral to anhedral, is shock metamorphosed into “maskelynite”. However, a few areas in plagioclase show weak birefringence that suggests the presence of crystalline plagioclase. It is unclear whether this is due to weaker shock effects compared to other shergottites or to minor annealing effects after amorphization by shock. Grain sizes of plagioclase are slightly larger than that of pyroxene. Rubin *et al.* (2000a) reported that average grain size of Los Angeles plagioclase is 0.5 × 2.5 mm. The thin section studied shows similar plagioclase sizes. Plagioclase composition varies from $An_{57}Ab_{42}Or_1$ to $An_{40}Ab_{52}Or_8$, which extends to slightly more Ab-Or-rich compositions than the other shergottite plagioclases (*e.g.*, Mikouchi *et al.*, 1999). Many plagioclase grains do not display complete concentric compositional zones. Instead, the most calcic part is commonly near a pyroxene grain boundary, and plagioclase is usually grown outward from that part. A few plagioclase grains appear to show normal core-to-rim chemical zoning. FeO abundance is 0.4–0.6 wt%.

3.3. Late-crystallization products

Los Angeles contains large areas of late-stage crystallization products. Most dominant phases are complex sinuous mixture of hedenbergite, fayalite, and silica that are similar to those found in lunar rocks and interpreted to be a breakdown product of pyroxferroite (Fig. 3) (Lindsley *et al.*, 1972; Rubin *et al.*, 2000a,b). Typical sizes of each constituent phase are about 5 μm. Silica is smaller in size and abundance compared to the other two constituents. Pyroxferroite breakdown products are usually associated with ulvöspinel, Ca phosphates, or K-rich feldspathic glass. Fayalite sometimes develops along the boundaries between these two areas. Silica contains 1–2 wt% Al_2O_3 and is probably tridymite. Fayalitic olivine compositions range $Fa_{90\text{-}95}$ and contain 1 wt% MnO, 0.3 wt% TiO_2, and 0.3 wt% CaO. Hedenbergite includes about 0.5 wt% Al_2O_3 and 0.5 wt% TiO_2 wt%, respectively. A pyroxene quadrilateral of Los Angeles shows the presence of the compositional cluster near $Ca_{15}Mg_5Fe_{80}$ (Fig. 2b), which is close to the composition of pyroxferroite (Lindsley *et al.*, 1972). It appears that they are from pyroxferroite that survived breakdown to hedenbergite + fayalite + silica, although the volume is minor. Thus, most pyroxferroites were decomposed into hedenbergite + fayalite + silica.

Large silica grains reaching 1 mm are present. They display only very weak birefringence with linear structures, suggesting that they are tridymite rather than quartz. These silica grains contain about 2 wt% Al_2O_3 and 0.5 wt% Na_2O. In many cases silica is adjacent to K-rich feldspathic glass. K-rich feldspathic glass shows dark appearance due to the presence of many small dark blebs. K-rich feldspathic glass contains up to 13 wt% Al_2O_3, 6 wt% K_2O and 2 wt% Na_2O.

Ulvöspinel is the most dominant opaque phase in Los Angeles. It contains 69 wt%

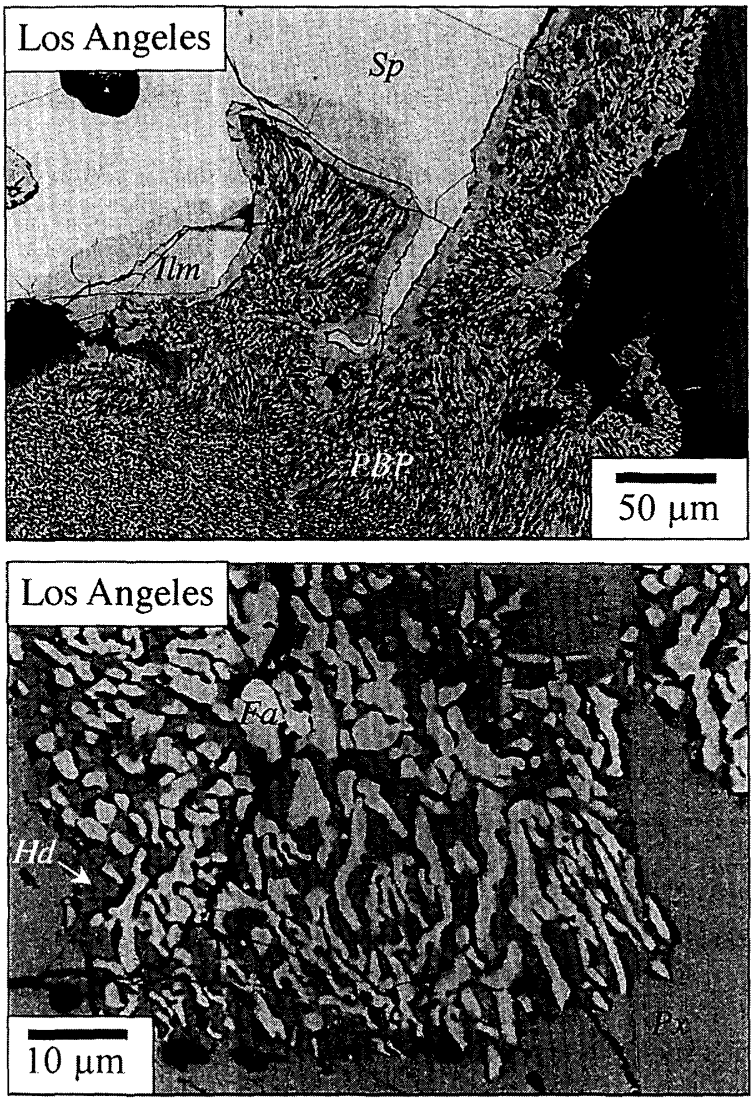


Fig. 3. BSE images of hedenbergite-fayalite-silica assemblages of Los Angeles, showing complex dendritic textures. They are usually associated with ulvöspinel, Ca phosphates, or some other late-crystallization phases. Sp: ulvöspinel. Ilm: ilmenite. Hd: hedenbergite. Fa: fayalite. Si: silica. Px: pyroxene.

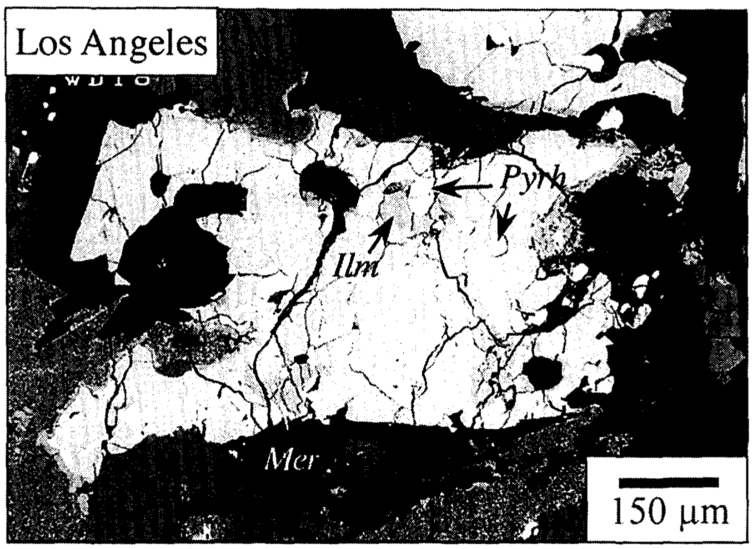


Fig. 4. BSE image of ulvöspinel enclosing pyrrhotite blebs and ilmenite patches. Ilm: ilmenite. Pyrh: pyrrhotite. Mer: merrillite.

FeO, 25 wt% TiO_2, 1.5 wt% Al_2O_3, and 1 wt% V_2O_3. Ulvöspinel often contains many pyrrhotite blebs and a few ilmenite patches (Fig. 4). Ulvöspinel also contains fine exsolution lamellae ($<1\,\mu$m) parallel to three directions (probably {111}) similar to the QUE94201 ulvöspinel.

Ca phosphates are merrillite and apatite. Merrillite sometimes encloses rounded inclusions of K-rich feldspathic glass, Al-rich pyroxenes and ulvöspinel. Merrillite includes 5 wt% FeO and 1 wt% MgO and 1 wt% Na_2O. Apatite only includes ~1 wt% FeO and trace amounts (<0.1 wt%) of MgO and Na_2O. EDS analysis shows that Ca phosphates are enriched in Cl.

4. Comparison with other basaltic shergottites and lunar mare meteorites

4.1. Los Angeles vs. "oxidized" shergottites (Shergotty and Zagami)

The coarse-grained texture of Los Angeles is clearly different from "classic" basaltic shergottites, Shergotty and Zagami except for the coarse-grained lithology and melt pockets in Zagami (McCoy *et al.*, 1999). The modal abundances of minerals are also different between Los Angeles and Shergotty/Zagami (Table 2). Pyroxene zoning patterns of Los Angeles are distinct from those of Shergotty and Zagami, but it is similar that pyroxenes are present as blocky grains composed of magnesian cores of pigeonite and augite rimmed by Fe-rich overgrowth (Mikouchi *et al.*, 1999). The plagioclase mineralogy of Los Angeles is also similar to those of Shergotty and Zagami (Mikouchi *et al.*, 1999). Another similarity between these shergottites is fO_2 during their formation. Los Angeles is estimated to have formed near the quartz-fayalite-magnetite buffer (Rubin *et al.*, 2000a,b; Herd and Papike, 2000). This is close to those of Shergotty and Zagami (*e.g.*, McSween, 1994; Herd and Papike, 2000).

The coarse-grained lithology and melt pockets found in Zagami (McCoy *et al.*, 1999) shows a close affinity to Los Angeles in many respects. They contain abundant hedenbergite-fayalite-silica assemblage, mesostases, phosphates, Fe-Ti oxides and sulfides (McCoy *et al.*, 1999). McCoy *et al.* (1999) suggested that the presence of a few kinds of different lithologies in Zagami could be explained by progressive fractional crystallization. McCoy *et al.* (1999) also suggested that the hedenbergite-fayalite-silica assemblages are products of primary crystallization after the magma enriched in iron to the point where low-Ca pyroxene was no longer a stable phase in contrast to the idea of their formation by breakdown of pyroxferroite (*e.g.*, Lindsley *et al.*, 1972; Rubin *et al.*,

Table 2. Modal abundances of minerals in some martian and lunar basalts.

	Los Angeles (Mars)	Shergotty* (Mars)	Zagami* (Mars)	QUE94201* (Mars)	Asuka-881757** (Moon)	Yamato-793169*** (Moon)
Pyroxenes	41.6	69.0	79.0	43.0	59.0	56.0
Plagioclase	45.0	26.0	17.0	43.0	30.0	42.0
Ca phosphates	2.3	2.0	2.0	6.0	-	-
Oxides	2.0	2.0	1.0	4.0	6.0	2.0
Others	8.8	1.0	1.0	4.0	5.0	-

*Mikouchi *et al.* (1999). **Yanai (1991). ***Takeda *et al.* (1993). -: Only trace amounts.

2000a,b). Because Zagami melt pockets contain more variations of assemblages including Ca phosphates and opaques, the McCoys' idea may be probable. However, because of simpler mineralogy of the hedenbergite-fayalite-silica assemblage in Los Angeles and the presence of original pyroxferroite, I prefer its formation by breakdown of pyroxferroite. At any rate, the Zagami melt pocket appears clearly related to Los Angeles as they have similar crystallization ages (Nyquist *et al.*, 2000).

4.2. Los Angeles vs. QUE94201

QUE94201 has similar modal abundances of minerals (especially, pyroxene-plagioclase ratio and abundant late-crystallization phases) to Los Angeles (Table 2) as well as its coarse-grained texture (Fig. 5). In spite of the broad similarities between Los Angeles and QUE94201, there are apparent differences between the two in textural respects. First, plagioclase morphology shows minor difference. Plagioclases in Los Angeles display subhedral to anhedral grain shapes, whereas plagioclases in QUE94201 are rather euhedral to subhedral. The zoning pattern of plagioclase in Los Angeles is also different from that of QUE94201. QUE94201 plagioclase shows typical core-to-rim zoning (Mikouchi *et al.*, 1999). The compositional range of Los Angeles plagioclase is $An_{57}Ab_{42}Or_1$ to $An_{40}Ab_{52}Or_8$. The most calcic plagioclase (first crystallized plagioclase) in QUE94201 is $An_{65}Ab_{35}Or_0$ and zoned to the $An_{59}Ab_{40}Or_1$ rims. The range is much narrower than that of Los Angeles. FeO content of the Ca-rich plagioclase in Los Angeles is a little higher (0.4–0.5 wt%) than that of Los Angeles (0.3 wt%).

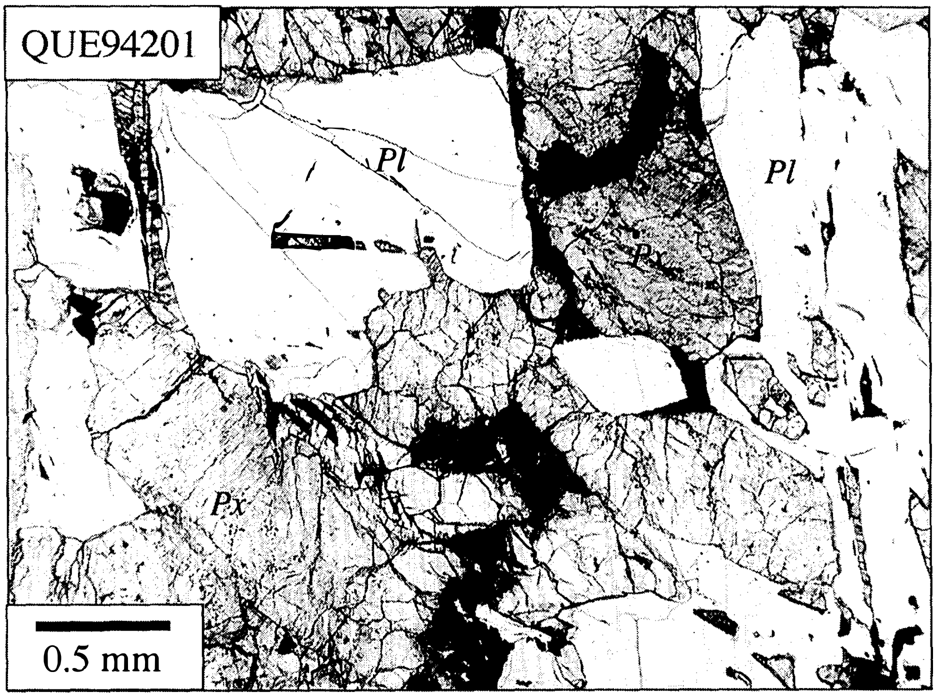


Fig. 5. Photomicrograph of QUE94201. The scale bar is 0.5 mm. QUE94201 shows a coarse-grained basaltic texture composed of subequal amounts of pyroxene and plagioclase similar to Los Angeles. Px: pyroxene. Pl: plagioclase.

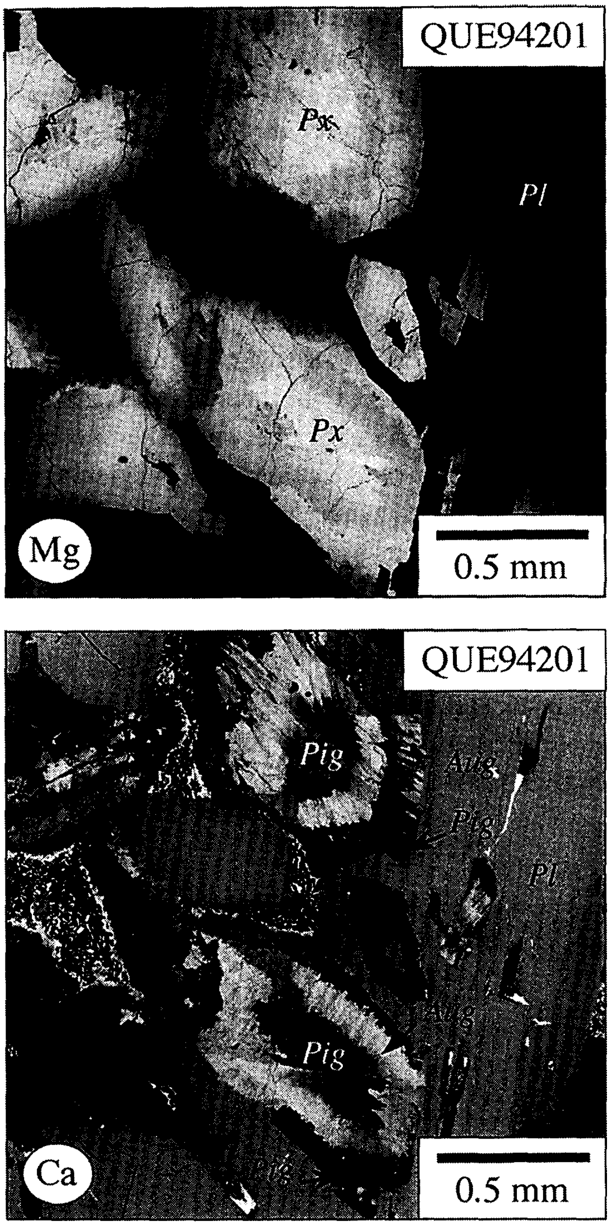


Fig. 6 (a). Mg and Ca X-ray Kα distribution maps of QUE94201. The scale bars are 0.5 mm. Each pyroxene grain is composed of magnesian pigeonite core mantled by magnesian augite parallel to {110}. The rim is Fe-rich pigeonite. Px: pyroxene. Pl: plagioclase. Pig: pigeonite. Aug: augite.

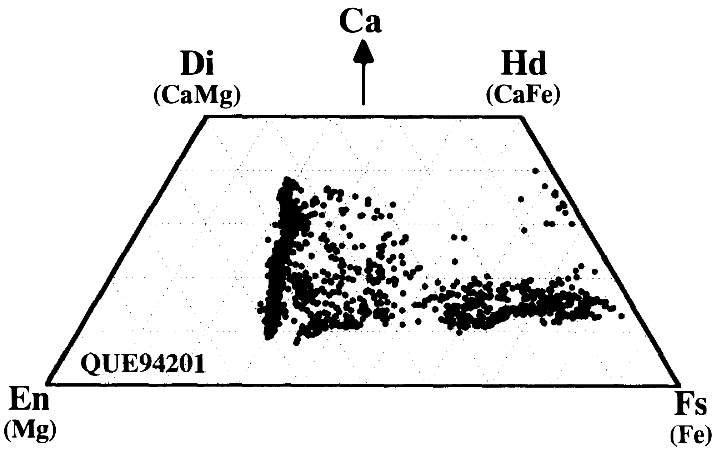


Fig. 6 (b). Pyroxene quadrilateral of QUE94201. The compositions extend to very Fe-rich regions and general compositional distributions are similar to those of Los Angeles.

The zoning patterns of Los Angeles pyroxenes (Fig. 2b) are similar to those of QUE94201 pyroxenes when they are plotted on pyroxene quadrilaterals (Fig. 6b). However, the spatial distributions of low- and high-Ca pyroxenes within one pyroxene grain are different between two meteorites (Fig. 6a). In Los Angeles, magnesian cores of pigeonite and augite are rimmed by Fe-rich pigeonite (Fig. 2a). Their distribution is complex and does not show clear crystallographic control. In contrast, QUE94201 pyroxenes show the sequence of different pyroxene crystallization in one crystal, starting from magnesian pigeonite cores, followed by magnesian augite mantles parallel to {110}, and ferroan pigeonite at the rims (Fig. 6a) (*e.g.*, Mikouchi *et al.*, 1998, 1999). Minor element distributions in pigeonites also show difference between Los Angeles and QUE94201. Furthermore, Los Angeles pyroxenes are more Fe-rich than QUE94201 pyroxenes. The most magnesian pigeonite cores of Los Angeles are *fe*# of 0.42, whereas those of QUE94201 are *fe*# of 0.33.

QUE94201 is distinct from Los Angeles in that abundant hedenbergite-fayalite-silica mixtures are rare in QUE94201, although QUE94201 preserves original pyroxferroite (McSween *et al.*, 1996). This means that a cooling rate of QUE94201 was faster than that of Los Angeles that allows preservation of pyroxferroite (Lindsley *et al.*, 1972).

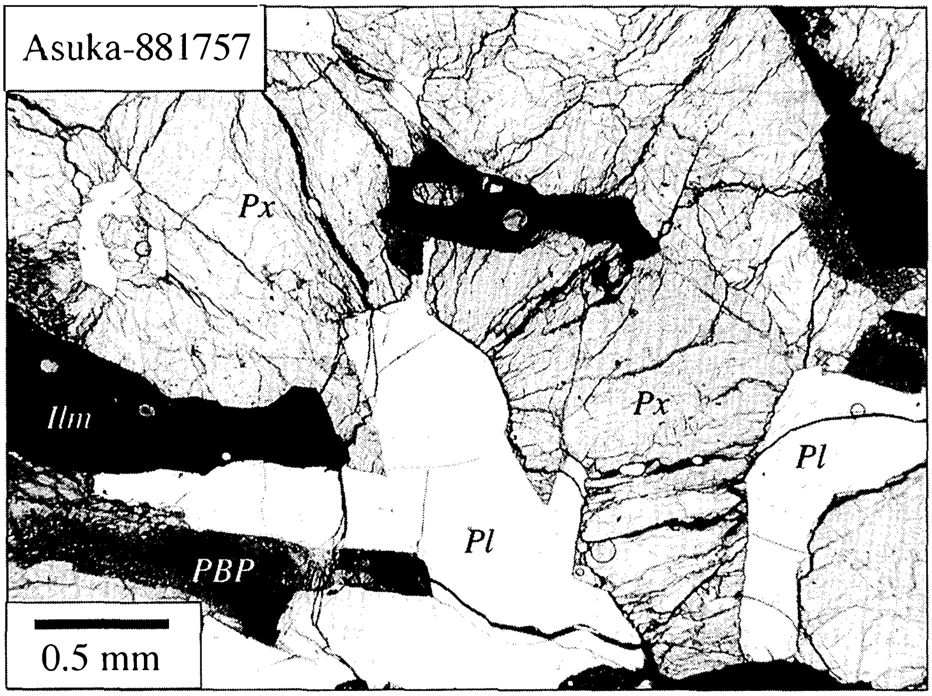
4.3. Los Angeles vs. lunar mare meteorites

Another close analogue to Los Angeles can be found in lunar mare meteorites. Asuka-881757 and Yamato-793169 are unbrecciated lunar mare meteorites showing basaltic textures mainly composed of pyroxene and plagioclase (*e.g.*, Yanai, 1991; Takeda *et al.*, 1993) (Figs. 7a, 7b). Modal abundances of minerals in these meteorites, especially Yamato-793169, are broadly similar to those of Los Angeles, although plagioclases are slightly less abundant than Los Angeles (Table 2). Pyroxene and plagioclase grain sizes of Yamato-793169 are not as large as those of Los Angeles, but Asuka-881757 is a coarse-grained basaltic rock whose average grain sizes reach 1 mm. Furthermore, Asuka-881757 contains abundant complex hedenbergite-fayalite-silica mixtures and large ulvöspinel-ilmenite grains (though pyrrhotite blebs are absent unlike Los Angeles) that are similar to those in Los Angeles.

Pyroxenes in Asuka-881757 and Yamato-793169 lunar mare meteorites are Fe-rich and also show generally similar chemical zoning patterns to Los Angeles as shown in pyroxene quadrilaterals (Figs. 8a, 8b). In addition, the spatial distributions of major elements are similar to Los Angeles (Figs. 9a, 9b). Pyroxenes are present as blocky grains composed of magnesian cores of pigeonite and augite rimmed by Fe-rich pigeonite. The most magnesian cores of Los Angeles pigeonites (*fe*# = 0.44) are intermediate between those of Asuka-881757 (*fe*# = 0.5) and Yamato-793169 (*fe*# = 0.39). Al and Ti distributions of these lunar pyroxenes are also generally similar to those in Los Angeles. Al shows decrease from core to rim, whereas Ti increases towards the rim. Furthermore, both pyroxenes show similar exsolution features. Asuka-881757 contains coarse exsolution lamellae (~0.5 μm wide) from the standard of lunar mare basalt (Arai *et al.*, 1996) (Fig. 10). Los Angeles pyroxenes have similar size and textures of exsolution lamellae, though some of them reach up to a few μm wide (Fig. 9a).

Plagioclase in lunar mare meteorites is Na depleted (usually $An_{\sim 90}$) and is quite

(a)



(b)

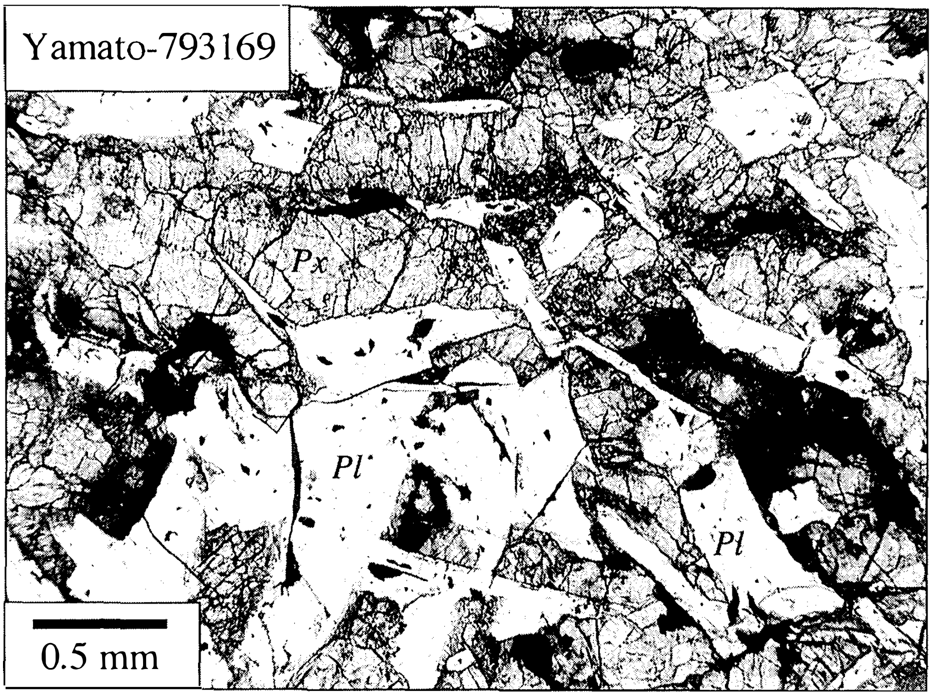


Fig. 7. (a) Photomicrograph of Asuka-881757. The scale bar is 0.5 mm. Asuka-881757 is also a coarse-grained basalt similar to Los Angeles and QUE94201. Wormy symplectites are observed near oxides. Px: pyroxene. Pl: plagioclase. Ilm: ilmenite. PBP: pyroxferroite breakdown products. (b) Photomicrograph of Yamato-793169. The scale bar is 0.5 mm. Yamato-793169 is finer-grained relative to Asuka-881757, but is composed of subequal amounts of pyroxene and plagioclase. Px: pyroxene. Pl: plagioclase.

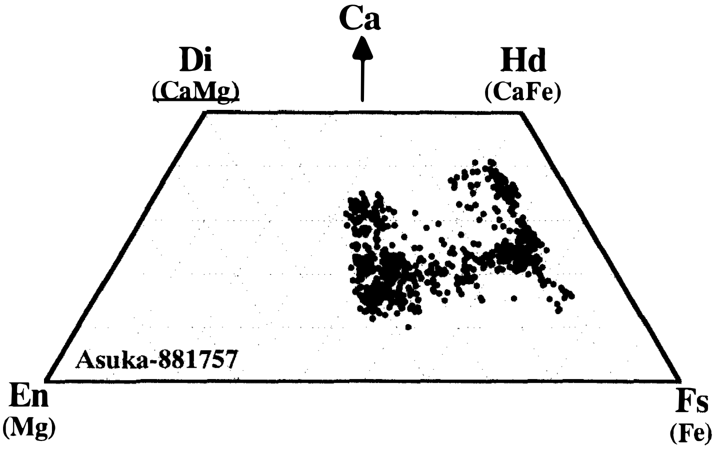


Fig. 8 (a). Pyroxene quadrilateral of Asuka-881757. Asuka-881757 pyroxene also shows similar compositional distributions to Los Angeles.

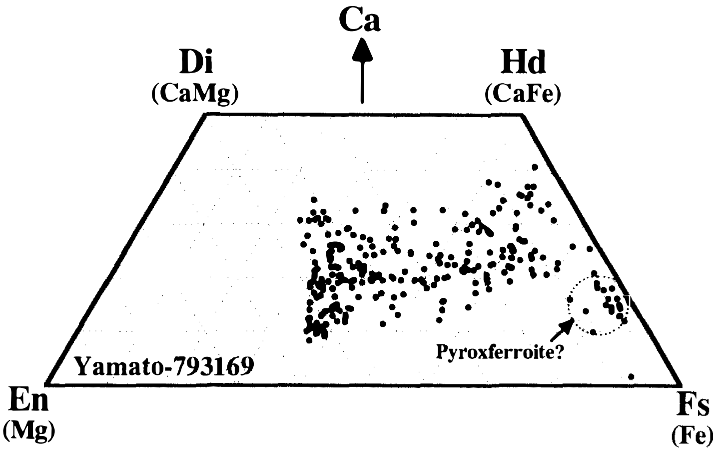


Fig. 8 (b). Pyroxene quadrilateral of Yamato-793169. Low-Ca and Fe-rich compositions may correspond to pyroxferroite like Los Angeles.

different from Martian plagioclase (usually $An_{\sim 50}$) in composition. Therefore, I only compare their morphology and growth texture. Plagioclase in Asuka-881757 shows large grain sizes and is subhedral to anhedral. The growth texture of plagioclase is also similar to Los Angeles. That is, the most calcic part is commonly near a pyroxene grain boundary and the plagioclase is usually grown outward from that calcic part (Mikouchi, 1999). Plagioclase in Yamato-793169 shows rather euhedral to subhedral lathy shapes. The zoning pattern is a normal core-to-rim type. It is also interesting that both Los Angeles and Asuka-881757 experienced strong shock effects, and plagioclase in these meteorites are transformed to "maskelynite" (Mikouchi, 1999).

Pyroxferroite was first discovered in lunar rocks, and it is only stable at pressures $\geqq$10 kbar (Lindsley and Burnham, 1970). Lindsley *et al.* (1972) performed heating experiments of pyroxferroite at 900°C and 1 bar for three days and found that pyroxferroite broke down to fayalite, hedenbergite and tridymite. Asuka-881757 contains large areas of complex mixtures (symplectites) of the hedenbergite-fayalite-silica assemblage, presumably the breakdown product of pyroxferroite (Fig. 11) as is observed in some other brecciated lunar mare meteorites (*e.g.*, Takeda *et al.*, 1992). Yamato-793169 does not contain large areas of these assemblages. In lunar meteorites, a few other minerals (plagioclase, Ca-poor pyroxene, apatite, Fe metal, ilmenite, ulvöspinel) are sometimes contained in the typical hedenbergite-fayalite-silica assem-

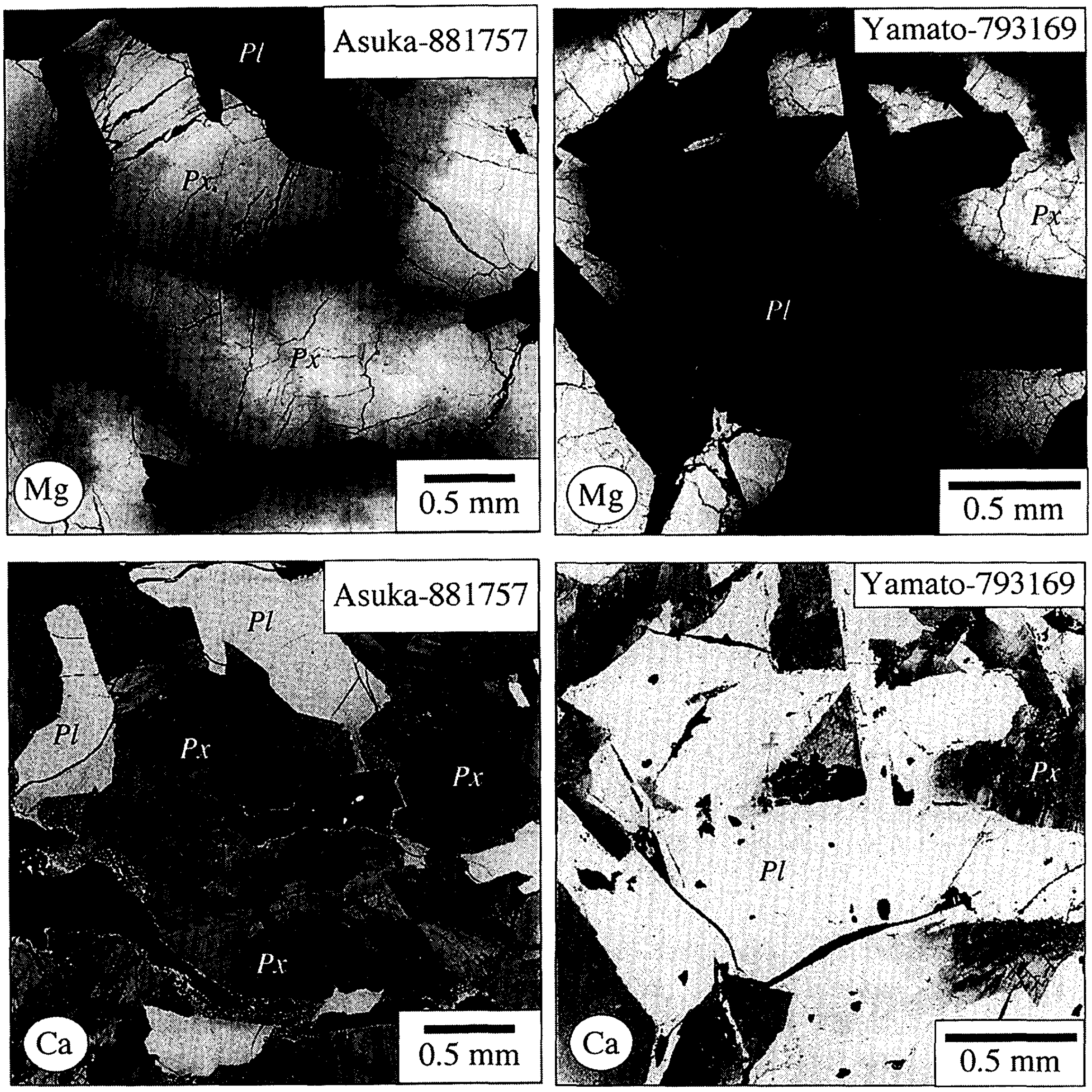


Fig. 9. (a) Mg and Ca X-ray Kα distribution maps of Asuka-881757. The scale bars are 0.5 mm. Pyroxenes show very complex chemical zoning similar to Los Angeles. In some areas, coarse exsolution features are visible. Px: pyroxene. Pl: plagioclase. (b) Mg and Ca X-ray Kα distribution maps of Yamato-793169. The scale bars are 0.5 mm. Pyroxene zoning is similar to Asuka-881757. Px: pyroxene. Pl: plagioclase.

blage like Zagami melt pockets (McCoy *et al.*, 1999). They are usually associated with late-crystallization phases (*e.g.*, ilmenite, ulvöspinel). Takeda *et al.* (1993) interpreted that they are late-stage decomposition products of Fe-rich metastable pyroxene. Kobayashi and Oba (2000) proposed that Asuka-881757 symplectites were produced by a meteorite impact at high pressure and temperature. However, it seems more likely that they are breakdown products of pyroxferroite during slow cooling as Lindsley *et al.* (1972) experimentally reproduced them. Another possibility is that they are products of primary crystallization after the magma enriched in iron to the point where low-Ca

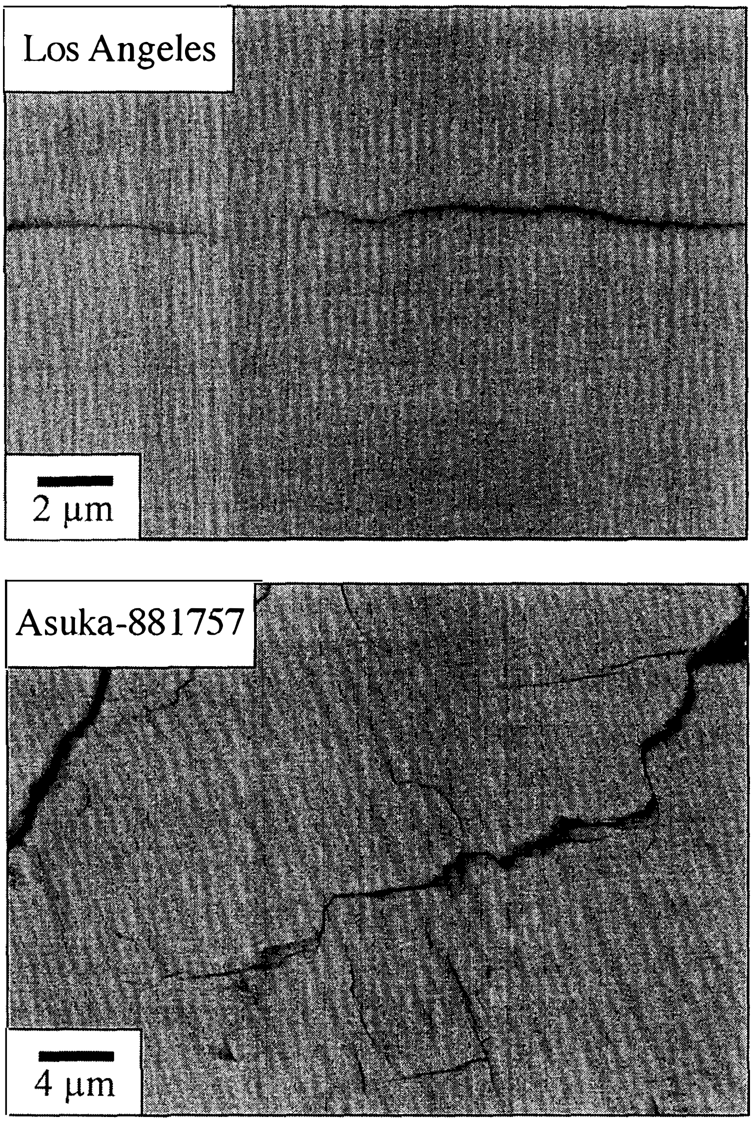


Fig. 10. High magnification BSE images of Los Angeles and Asuka-881757 pyroxenes. Both meteorites show pyroxene exsolution features of similar lamellar widths. This is consistent with major element distributions within pyroxenes (Figs. 2, 8).

pyroxene was no longer a stable phase as is suggested by McCoy *et al.* (1999). The maskelynitization of plagioclase probably occurred when it was ejected from the Moon by impact. The Asuka-881757 symplectite is sometimes faulted (Fig. 11), suggesting that the symplectite formation was prior to the impact as suggested by Rubin *et al.* (2000a,b) and Greenwood *et al.* (2000). The texture of Asuka-881757 symplectite shows that fayalite and silica are associated with each other (Fig. 11). This may imply that pyroxferroite was first decomposed into hedenbergite and Ca-poor ferroan pyroxene, and then Ca-poor ferroan pyroxene was decomposed into fayalite and silica. There is a minor difference in features of these hedenbergite-fayalite-silica assemblages between Los Angeles and Asuka-881757. In Los Angeles, the hedenbergite-fayalite-silica areas usually have these minerals in 2 : 2 : 1 proportion. In contrast, the hedenbergite-fayalite-silica areas in Asuka-881757 typically contain more hedenbergite than fayalite, and in some cases only very minor silica (Koeberl *et al.*, 1993).

In spite of small differences, both Los Angeles and Asuka-881757 are similar in the presence of large areas of the fayalite + hedenbergite + silica assemblage, presumably to

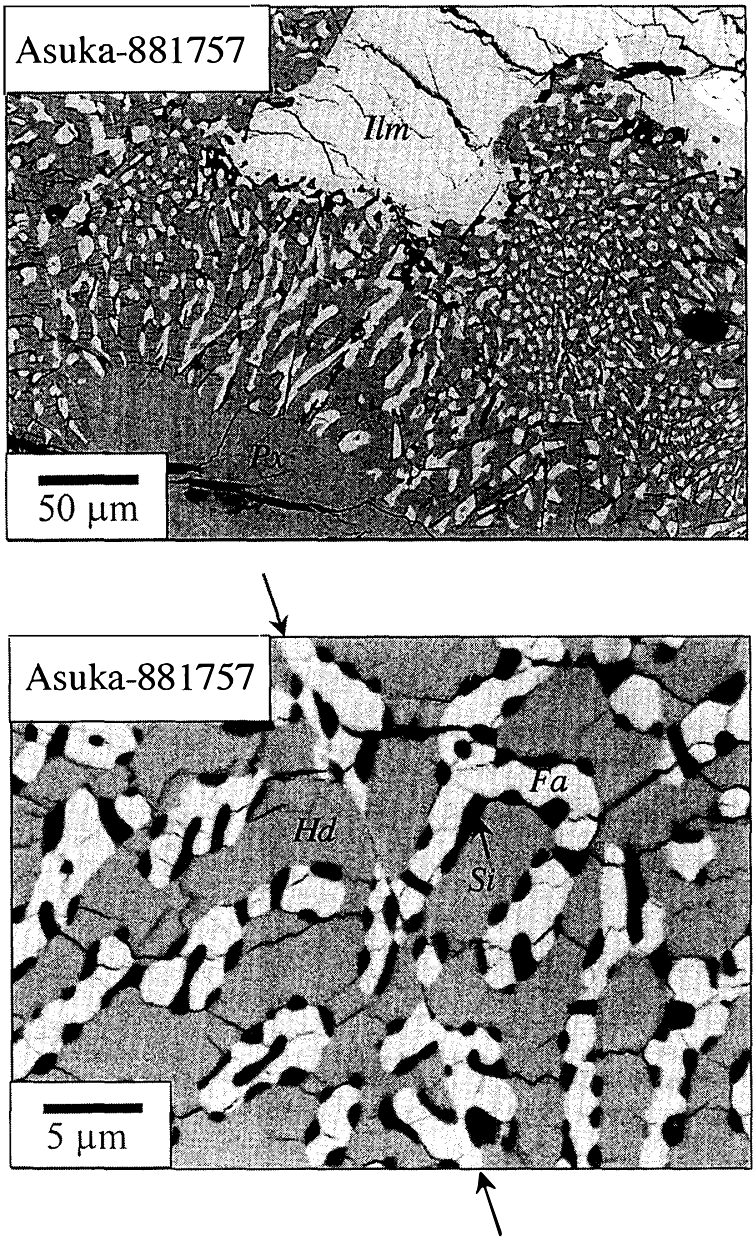


Fig. 11. BSE images of fayalite-hedenbergite-silica assemblages in Asuka-881757. Silica is usually located at the edges of sinuous-shaped fayalite, suggesting secondary decomposition into fayalite and silica. The fayalite-hedenbergite-silica assemblage (lower image) is faulted probably due to shock (indicated by arrows). Px: pyroxene. Ilm: ilmenite. Fa: fayalite. Hd: hedenbergite. Si: silica.

be the breakdown product of pyroxferroite. The presence of these breakdown products suggests that both meteorites cooled from ~1200°C to 900°C for a period longer than three days (Lindsley *et al.*, 1972), corresponding to a maximum cooling rate of about 4°C /hour.

4.4. Crystallization from differentiated magmas on Mars and the Moon

As described above, Los Angeles shows close mineralogical properties to lunar mare meteorites, especially Asuka-881757, rather than previously known basaltic shergottites (except for Zagami melt pockets). These similarities probably reflect the similar formation conditions of these two meteorites, despite being from different planetary bodies (Mars *vs*. the Moon). Between these two bodies, one of the most significant differences is the presence or absence of water in the magmas from which they crystallized. There is no doubt that lunar parent magmas did not contain any water. Some Martian meteorites contain hydrous minerals such as kaersutite and some of their parent melts are believed to contain some amounts of water (*e.g.*, McSween, 1994). However, no evidence for water is found in Los Angeles or QUE94201 because no hydrous phases were identified in these meteorites. McCoy *et al.* (1999) also suggested that the water-poor nature of the late-stage melt pockets in Zagami implies crystallization from a very dry magma. Probably, all these shergottites crystallized from dry magmas like lunar mare basalts. The other significant difference between Martian and lunar basalts is different fO_2 during crystallization. Wadhwa *et al.* (1998) compared QUE94201 and lunar basalt 15555 and pointed out that fO_2 conditions during QUE 94201 crystallization were significantly more reducing than for other shergottites, although not quite as reducing for lunar basalts. The estimated fO_2 of Los Angeles is near the quartz-fayalite-magnetite buffer (Rubin *et al.*, 2000a,b; Herd and Papike, 2000). This is close to those of Shergotty and Zagami rather than that of QUE94201. Warren *et al.* (2000a) also suggested a Los Angeles genesis at a relatively high fO_2 by the REE pattern lacking any appreciable Eu anomaly. In these senses, Los Angeles formed at oxidizing conditions unlike either QUE94201 or lunar mare basalts. Warren *et al.* (2000a) also implied that trace element chemistry of Los Angeles is similar to Shergotty and Zagami rather than QUE94201, and concluded that Los Angeles is not igneously related to QUE94201. The crystallization age of Los Angeles (165 ± 11 Ma) agrees with these observations that Shergotty and Zagami might be petrogenetically related to Los Angeles (Nyquist *et al.*, 2000). The presence of melt pockets in Zagami showing similar mineralogy to Los Angeles (McCoy *et al.*, 1999) supports this scenario. Mikouchi *et al.* (1999) proposed that QUE94201 experienced rapid metastable cooling history whereas Shergotty and Zagami followed near-equilibrium cooling histories. The plagioclase growth feature of Los Angeles is similar to Shergotty and Zagami rather than QUE94201, although plagioclase abundance shows similarity between Los Angeles and QUE94201. Warren *et al.* (2000b) suggested that the earliest pyroxenes in Los Angeles may have been phenocrysts in relation to the parent melt for the remainder of the rock. In this respect, Los Angeles is different from QUE94201 and the bulk composition of Los Angeles does not preserve that of any single-parent melt (Warren *et al.*, 2000b), although heterogeneity of Los Angeles (Rubin *et al.*, 2000a,b) makes argument of its bulk composition difficult.

It is remarkable that pyroxenes in these two meteorites are fairly Fe-rich, implying that they crystallized from differentiated, ferroan magmas. Major element abundances will be also similar between parent magmas of these two meteorites as is suggested by their generally similar bulk compositions (Yanai and Kojima, 1991; Warren and Kallemeyn, 1993; Koeberl *et al.*, 1993; Warren *et al.*, 2000a; Rubin *et al.*, 2000b), although alkali elements were clearly depleted in lunar magmas. The Fe-enriched nature of pyroxenes in these two meteorites caused metastable crystallization of pyroxferroites, which broke down to fayalite + hedenbergite + silica upon slow cooling. The subsolidus cooling rates or degrees of re-equilibration are generally similar between Los Angeles and Asuka-881757 because of the similar widths of pyroxene exsolution lamellae (Fig. 10). However, the sizes of pyroxene breakdown products in Asuka-881757 are slightly larger than those of Los Angeles. Furthermore, there are no pyroxenes that plotted near the pyroxferroite composition in the pyroxene quadrilateral of Asuka-881757 (Fig. 8a). These may suggest that Asuka-881757 cooled somewhat slower than Los Angeles, allowing complete breakdown of pyroxferroite and growth of larger breakdown products.

5. Summary

A newly recovered basaltic shergottite Los Angeles shows the textural similarity to QUE94201. Both meteorites are composed of subequal amounts of Fe-rich pyroxene and plagioclase plus abundant late-crystallization phases. The chemical compositions of pyroxenes are generally similar between two meteorites. Nevertheless, they show apparent differences in the following respects: (1) Pyroxenes in Los Angeles are composed of magnesian pigeonite or augite cores rimmed by Fe-rich pigeonite and they are complexly intergrown with each other. (2) Plagioclase in Los Angeles is usually grown outward from the most calcic part near the pyroxene walls. (3) Los Angeles contains abundant hedenbergite-fayalite-silica assemblages that are interpreted to be breakdown products of pyroxferroite. These three properties are observed in lunar mare meteorite Asuka-881757, but no shergottites have all three in one sample except for Los Angeles. Probably, Los Angeles and Asuka-881757 experienced similar crystallization and cooling histories although they came from different planetary bodies. They crystallized from dry, Fe-rich parent magmas of similar major element compositions except for alkalis. The fO_2 condition during Los Angeles formation is relatively oxidizing compared to Asuka-881757 formation.

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