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SHOCKED PLAGIOCLASE IN THE LUNAR METEORITES YAMATO-793169 AND ASUKA-881757: IMPLICATIONS FOR THEIR SHOCK AND THERMAL HISTORIES

Takashi MIKOUCHI

Mineralogical Institute, Graduate School of Science, University of Tokyo, Hongo, Bunkyo-ku, Tokyo 113-0033

***Abstract*:** Yamato (Y)-793169 and Asuka (A)-881757 are unbrecciated lunar mare meteorites that contain shocked plagioclase as a main constituent phase. Plagioclase in Y-793169 is composed of fine-grained microlitic grains that preserve the overall optical orientation of the original grain. Small vesicles are also observed within plagioclase grains. Plagioclase shows chemical zoning from the An-rich core (An_{96}) to the An-poor rim (An_{85}). These observations suggest that plagioclase in Y-793169 recrystallized from a diaplectic glass by thermal annealing as the heating experiment of a diaplectic plagioclase suggests. The thermal annealing event might occur sometime later than 750 Ma that has been derived from the K-Ar study of plagioclase. A-881757 plagioclase has completely transformed into an isotropic glass similar to "maskelynite" in Martian meteorites. Chemical zoning of plagioclase is well preserved, showing a systematic change of composition from the An-rich core (An_{95}) to the slightly An-poor rim (An_{90}). Plagioclase glass partly converts to crystalline (optically single crystal) plagioclase near the fusion crust due to reheating during the atmospheric entry. All of these observations suggest that plagioclase glass in A-881757 is probably a diaplectic glass. Unlike Y-793169, plagioclase glass in A-881757 has not been modified by later thermal events, which is consistent with the old ^{40}Ar-^{39}Ar age (3.8 Ga) of A-881757 plagioclase glass. Thus, Y-793169 and A-881757 contained (A-881757 still contains) a diaplectic plagioclase glass that was shock-induced perhaps during the late heavy bombardment of the Moon as their old crystallization ages (3.8-3.9 Ga) indicate.

1. Introduction

The total number of the meteorites from the Moon has been constantly growing by the meteorite recovery expeditions to Antarctica and African deserts and now it reaches fifteen (ZIPFEL *et al.*, 1998). It is sure that some of them are paired samples (*e.g.*, Y-82192, Y-89193 and Y-86032), but lunar meteorites still offer useful information on lunar science as the only available lunar samples after the Apollo and Luna missions. Most lunar meteorites, especially early recognized ones, are anorthostic breccias that have originated from the highland and non-brecciated basaltic rocks from mare regions are rare. The Yamato-793169 (Y-793169) and Asuka-881757 (A-881757) lunar meteorites are the only such kind of meteorites that are non-brecciated crystalline rocks obviously of mare origins (*e.g.*, YANAI, 1991; YANAI and KOJIMA, 1991). By the recent extensive consortium studies organized by National Institute for Polar Research

(NIPR), many interesting characteristics in chemistry and mineralogy have been revealed for Y-793169 and A-881757. Both of them (especially, A-881757) are significantly coarse-grained rocks by mare rock standards that are mainly composed of pyroxene and plagioclase (*e.g.*, Yanai, 1991; Yanai and Kojima, 1991; Takeda *et al.*, 1993). Now they are believed to represent a new type of mare basalt in spite of chemical (major element) and petrological affinities to very low-Ti (VLT) and low-Ti (LT) mare basalts found in the Apollo and Luna samples (*e.g.*, Misawa *et al.*, 1993; Koeberl *et al.*, 1993; Takeda *et al.*, 1993; Warren and Kallemeyn, 1993; Torigoye-Kita *et al.*, 1995; Arai *et al.*, 1996).

Although several petrological and mineralogical studies have been performed on these interesting rocks, they have mainly focused on pyroxenes and have not paid much attention to plagioclase. Plagioclase is one of the key minerals to draw shock and thermal history of the meteorites due to its sensitivity against such effects (*e.g.*, Ostertag and Stöffler, 1982, 1983; Bischoff and Stöffler, 1992). Because the isotopic age studies for Y-793169 and A-881757 give ancient ages (Y-793169: 3.8 Ga, A-881757: 3.9 Ga) (Misawa *et al.*, 1993; Torigoye-Kita *et al.*, 1995), they might have experienced severe shock events during the late heavy bombardment of the Moon (*e.g.*, Tera *et al.*, 1974). Lunar meteorites should have also experienced heavy impact events when they were ejected from the Moon. Therefore, it is important to study plagioclase in these basaltic rocks to understand their overall histories from their primary crystallization to recovery at Antarctica. Better understanding of the mineralogy of shocked plagioclase in these samples could also offer important clues to understand the nature of shocked plagioclase glass (maskelynite) in Martian meteorites including ALH84001, a controversial sample on the presence/absence of relic biogenic activity in the Mars rock (McKay *et al.*, 1996). It has been disputatious whether shocked plagioclase glass in meteorites is really a diaplectic glass or not by the recent suggestion that "maskelynite" in Shergotty Martian meteorite is a melt glass (El Goresy *et al.*, 1997a, b). In this paper, I use the term, "maskelynite", for the shocked plagioclase glass in Martian meteorites. At present lunar meteorites are the only extraterrestrial samples that we can compare with the real sample of the parent body that they have originated (it is Moon in this case). Therefore, it is possible to study mineralogical difference of the phases between original country rocks (Apollo and Luna samples) and shock-ejected rocks (lunar meteorites).

This paper presents a detailed mineralogical investigation of plagioclase (glass) in Y-793169 and A-881757 lunar meteorites and discusses their shock and thermal history.

2. Samples and Analytical Techniques

Polished thin sections of Y-793169 (Y-793169,51-3) and A-881757 (A-881757,51-4) were supplied by NIPR. In order to perform a comparative study, I also analyzed several Martian meteorites. Some of them were supplied by NIPR and The Meteorite Working Group (MWG) at NASA Johnson Space Center. Petrographic observations and mineral analyses were made on the thin sections by optical and electron microscopy. The electron microscopy was performed by JEOL JXA 840 scanning electron microscope (SEM) and Hitachi S-4500 field emission gun SEM (Mineralogical Inst., Univ. of

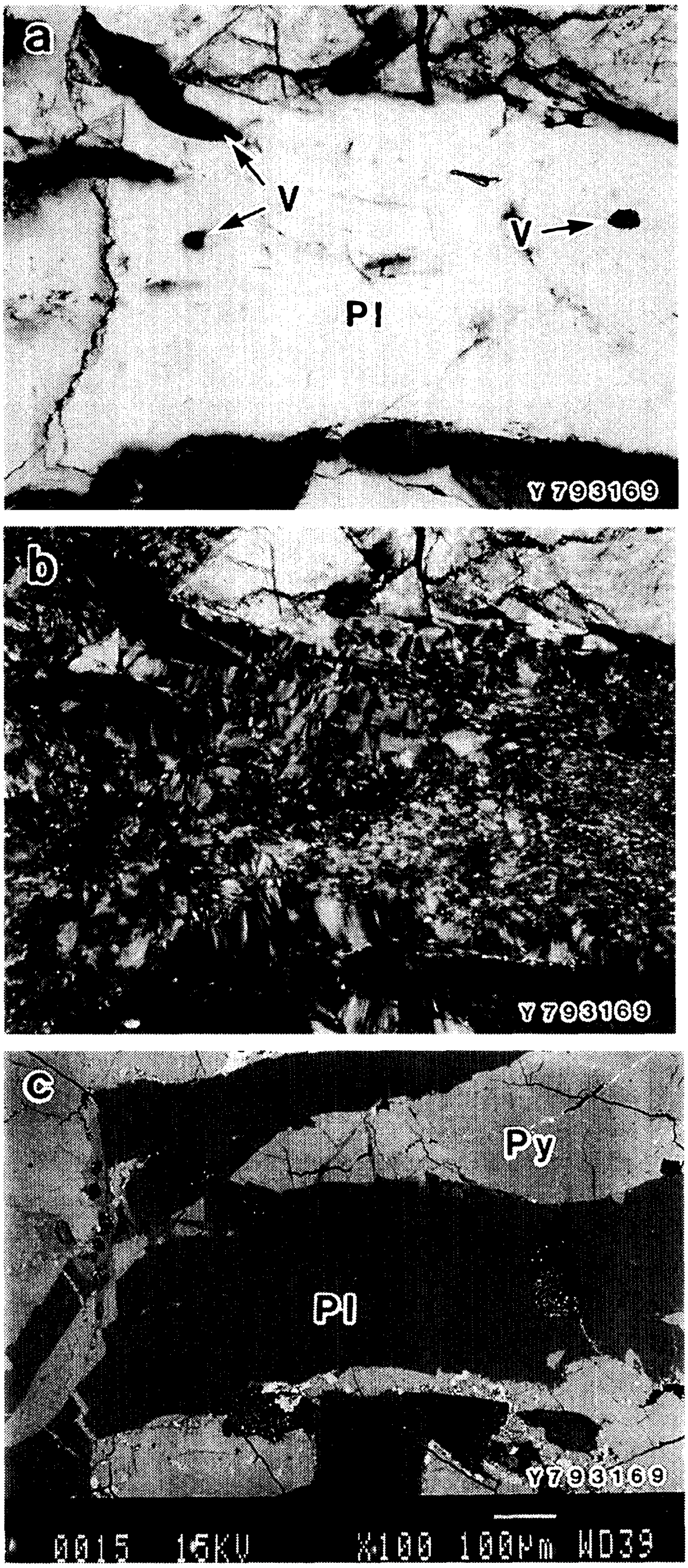

Fig. 1. Optical and backscattered electron (BSE) photomicrographs of Y-793169 lunar meteorite. (a): plane-polarized light. (b): cross-polarized light. (c): BSE image. The field of view is about 0.6 mm for (a) and (b). It is clear from b that plagioclase is composed of very fine-grained plagioclase domains. Some show acicular growth from the pyroxenes. A few vesicles are seen within the plagioclase grain. Pl: plagioclase. Py: pyroxene. V: vesicle.

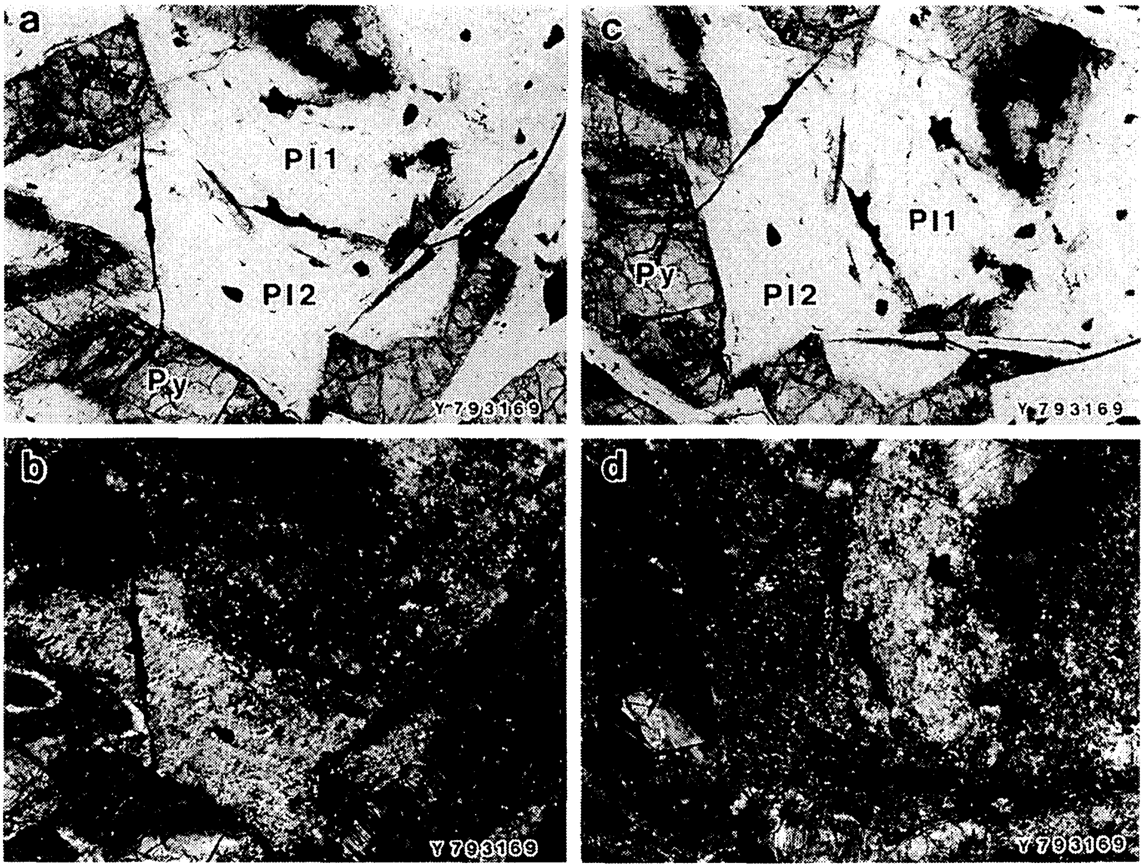

Fig. 2. Optical photomicrographs of Y-793169 lunar meteorite. (a) and (c): plane-polarized light. (b) and (d): cross-polarized light. The field of view is about 1.2 mm, respectively. The angle between (a), (b) and (c), (d) is about 45°. Note that small plagioclase domains within the same grain have generally identical extinction angles. In (b), plagioclase grain (Pl1) shows nearly extinction, but the next plagioclase grain (Pl2) is at nearly diagonal position. In contrast, Pl1 is at a diagonal position and Pl2 is at an extinction position in (d). Pl1, Pl2: plagioclase. Py: pyroxene.

Tokyo). Quantitative wavelength dispersive analyses were performed on a JEOL 733 electron microprobe (Ocean Research Inst., Univ. of Tokyo) and a JEOL JCM 733 mk II microprobe (Geological Inst., Univ. of Tokyo). The microprobes were operated at 15 kV accelerating voltage and beam current was 8 nA on Faraday cages. To reduce volatile loss such as Na, defocused beam of 3–5 μm diameter was employed. Elemental distribution maps were obtained by a JEOL JXA 8900L electron microprobe (Geological Inst., Univ. of Tokyo). Accelerating voltage was 15 kV and beam current was 60 nA on a Faraday cage. I counted the element intensity at peak wavelength for 20 ms for each pixel of the measured area.

3. Results

3.1. Plagioclase mineralogy

3.1.1. Y-793169

Y-793169 is mainly composed of nearly equal amounts of pyroxene and plagioclase

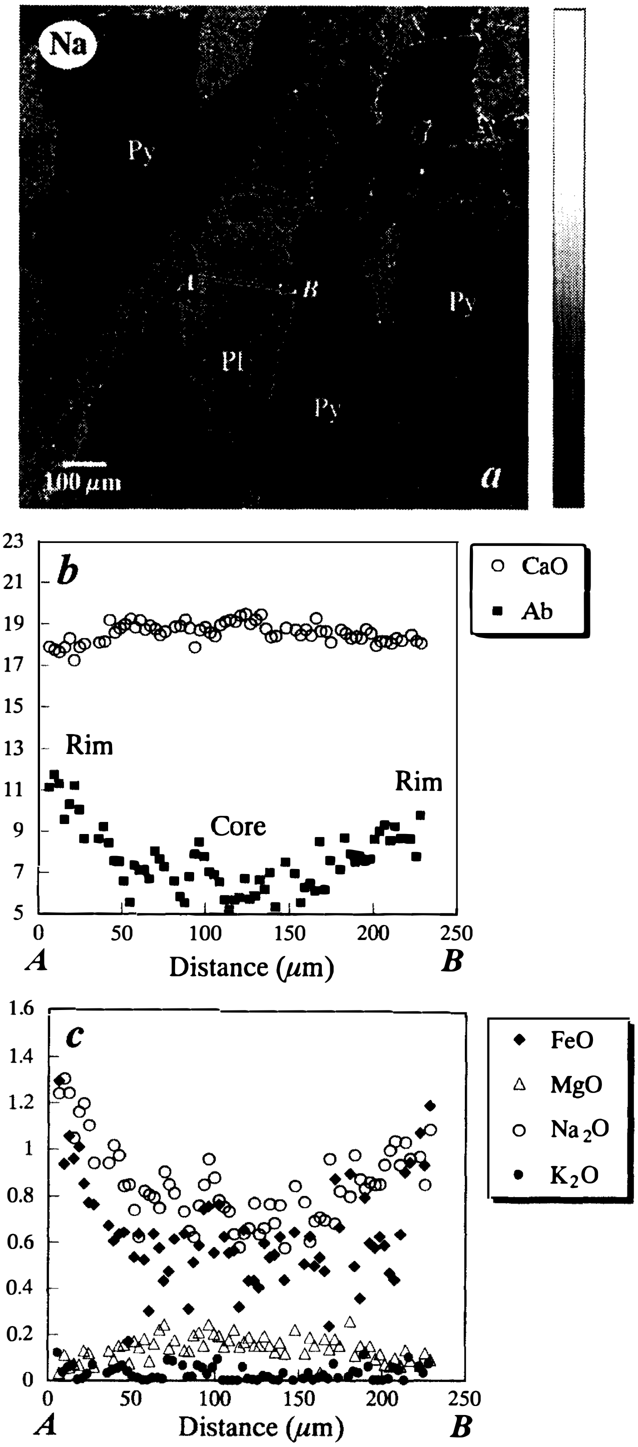

Fig. 3. Na X-ray map (a) and element zoning profiles (b and c) of Y-793169 plagioclase. (d) shows cation totals along the line. The zoning profiles are obtained from the grain shown near the center of (a). The arrow (A-B) shows a microprobe traverse. Na does not display clear zoning in the Na map (a), but is enriched at the rims. In spite of plagioclase recrystallization, the original plagioclase grain has chemical zoning similar to normal igneous zoning. Pl: plagioclase. Py: pyroxene.

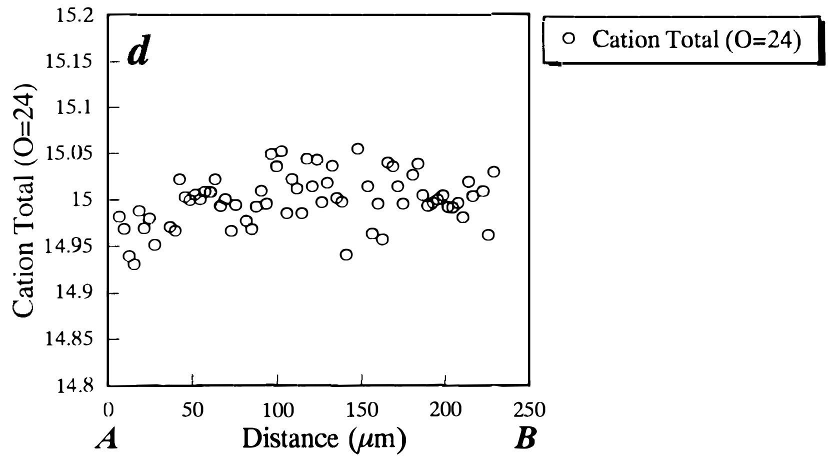

Fig. 3 (continued).

with minor mesostasis of the late-stage minerals (*e.g.*, ilmenite, spinel, fayalite). Pyroxenes are fairly Fe-rich and show complex zoning patterns and their compositions are scattered when they are plotted on a pyroxene quadrilateral as suggested by several workers (*e.g.*, Yanai and Kojima, 1991; Takeda *et al.*, 1993). Pyroxenes are often fractured and partly blackened as is often observed in pyroxene of Martian meteorites (*e.g.*, Shergotty). El Goresy *et al.* (1997a, b) suggested that fractures in pyroxenes of Martian meteorites are expansion cracks produced by volume increase due to relaxation of maskelynite after pressure release. Y-793169 pyroxene also shows undulatory extinction due to shock.

Plagioclases in Y-793169 are typically subhedral laths, reaching 1 mm in length. They are composed of fine-grained polycrystalline aggregates of plagioclase within each grain (Fig. 1). They are sometimes fibrous at the grain boundaries and clearly show nucleation from the grain boundaries (Fig. 1). Plagioclase itself rarely contains fractures within the grain. Radiating fractures into the surrounding pyroxene grains develop in some areas although it is not so remarkable as is observed in maskelynite and pyroxene of Martian meteorites (El Goresy *et al.*, 1997a, b). The optical extinction angle of each microlitic plagioclase domain within the same plagioclase grain is generally identical in most grains (Fig. 2), probably maintaining the primary optical orientation of the original grain. Plagioclase contains small vesicles (~100 μm) that are usually rounded, but in some cases irregularly elongated (Fig. 1). The original plagioclase grains generally show overall chemical zoning in both major and minor elements that are similar to that of an igneous origin (Fig. 3). Its chemical composition is shown in Table 1. Major elements are usually zoned from the An_{96} core to the An_{85} rim. FeO, K_2O and MgO are minor components of calcic plagioclase, but they are also zoned from core to rim (Fig. 3). FeO shows systematic increase from core (0.4 wt%) to rim (~1.5 wt%). MgO is 0.2 wt% in the core regions and drops down to 0.05 wt% at the rims. K_2O is usually below detection limit of microprobe analysis, but some grains show enrichment (0.2 wt%) at the rims. Assuming that oxygen anion is 24, microprobe analysis shows that total cation of analyzed plagioclase is between 14.95 and 15.05, well matching with stoichiometric plagioclase (Fig. 3).

Table 1. Chemical composition of Yamato-793169 plagioclase.

	Core	Rim
SiO_2	45.62	47.52
TiO_2	0.03	-
Al_2O_3	34.16	32.41
FeO	0.51	0.93
MnO	0.03	0.09
MgO	0.19	0.10
CaO	19.15	17.69
Na_2O	0.61	1.30
K_2O	0.02	0.04
Cr_2O_3	-	-
V_2O_3	0.09	-
NiO	0.08	-
P_2O_5	-	-
Total	100.49	100.07
An	*94.43*	*88.07*
Ab	*5.48*	*11.71*
Or	*0.09*	*0.21*
Cation total	14.99	14.97

3.1.2. A-881757

A-881757 is more coarse-grained than Y-793169, but their textures are mostly similar to each other except for the grain sizes. Major constituent phases of A-881757 are pyroxene and plagioclase glass with 5–10 vol% of ilmenite plus minor amounts of spinel, troilite, olivine and some other trace phases. Pyroxenes are more Fe-rich than those in Y-793169, but generally their zoning patterns are similar. The range of major element compositions is slightly narrower than that of Y-793169 (*e.g.*, YANAI and KOJIMA, 1991; TAKEDA *et al.*, 1993). Pyroxenes are fractured and show undulatory extinction due to shock like Y-793169.

Plagioclase in A-881757 is an isotropic glass and optically amorphous (Fig. 4). It usually has smooth surface on the thin section and the inner fractures are not abundant. Radiating fractures into the surrounding pyroxene grains are more conspicuous than those from plagioclase in Y-793169. Such radiating fractures are especially found around the plagioclase glass that is completely surrounded by pyroxenes (Fig. 4). All of these characteristics resemble those of maskelynite in Martian meteorites (Fig. 5). However, unlike maskelynite in Martian meteorites, they partially convert to crystalline plagioclase with clear birefringence where they contact to the fusion crust (Fig. 6). In such a region, they are optically composed of single crystals (Fig. 6).

Plagioclase glass in A-881757 shows systematic chemical zoning from the An_{95} core to the An_{85} rim in many grains. In some regions, especially near the mesostasis, Na and K enrichment is observed (reaching $An_{74}Ab_{23}Or_3$). Its chemical composition is shown in Table 2. Most plagioclase grains show normal core-rim zoning (Fig. 7), but some

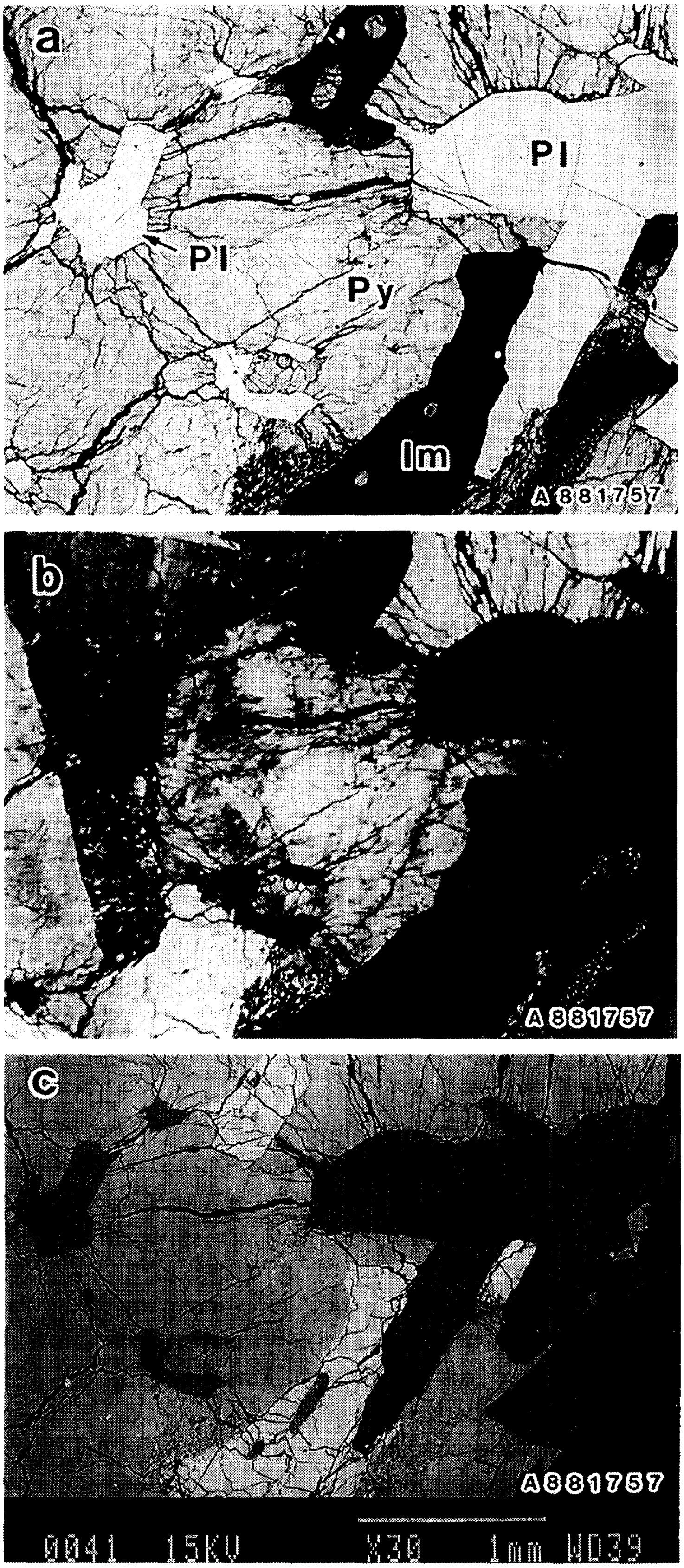

Fig. 4. Optical and BSE photomicrographs of A-881757 lunar meteorite. (a): plane-polarized light. (b): cross-polarized light. (c): BSE image. The field of view is about 3 mm for (a) and (b). As is clear from (b), plagioclase is completely isotropic in the crossed polarizers (b). Radiating fractures develop from plagioclase glass. Pl: plagioclase glass. Py: pyroxene. Im: Ilmenite.

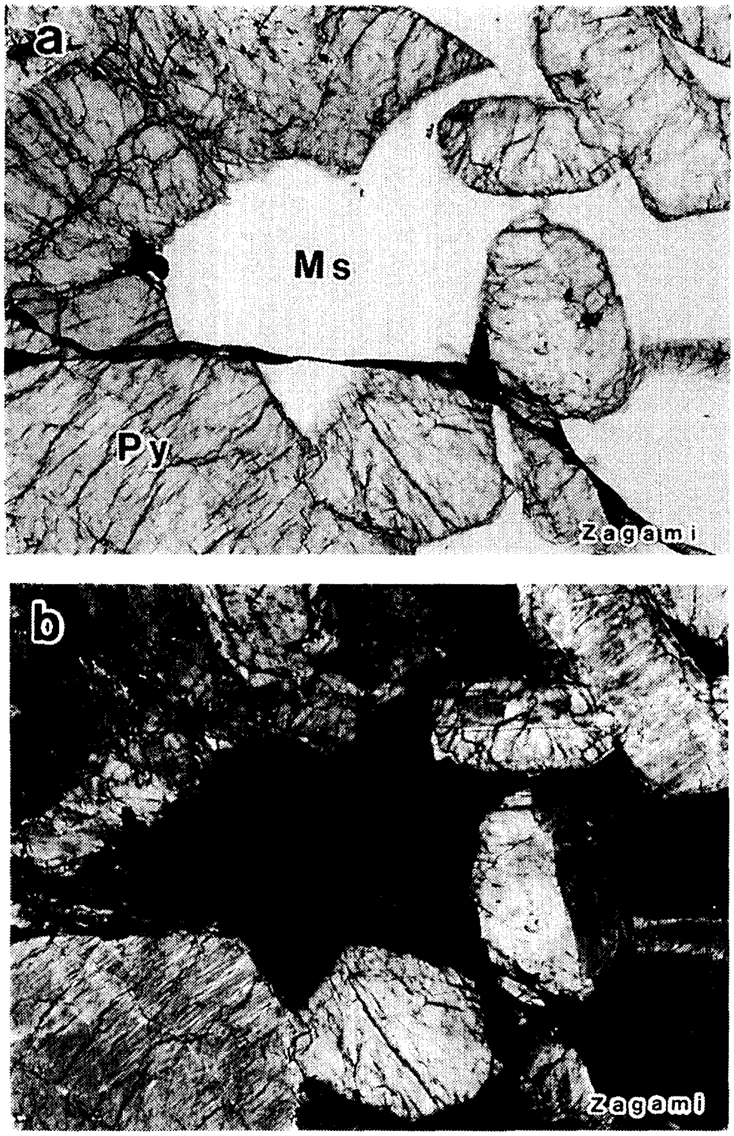

Fig. 5. Optical photomicrographs of Zagami Martian meteorite. (a): plane-polarized light. (b): cross-polarized light. The field of view is about 1.2 mm, respectively. Plagioclase is completely amorphous ("maskelynite") in the crossed polarizers (b). Radiating fractures develop from maskelynite like A-881757. Inner fractures are absent in maskelynite, showing smooth surface. Ms: plagioclase glass. Py: pyroxene.

shows nucleation on pyroxene and growth outwards from the pyroxene rim. Similar irregular chemical zoning is also observed in maskelynites of the Shergotty and Zagami Martian meteorites and they are considered to be of an igneous origin (Mikouchi *et al.*, 1997). Minor elements in plagioclase glass are also zoned (Fig. 7). FeO shows increase from core (0.4 wt%) to rim (1 wt%) while MgO is negatively related (core: 0.15 wt%, rim: < 0.05 wt%). K_2O usually increases from the nearly K-free cores to the rims of 0.3 wt%. Cation total usually does not show significant change and is stoichiometric plagioclase (Fig. 7). Compositional difference between amorphous and crystalline plagioclase near the fusion crust is absent as is shown in Fig. 8.

4. Implications for Shock and Thermal Histories

Although Y-793169 and A-881757 lunar meteorites share many common characteristics in mineralogy and major element chemistry, trace element concentration as well as

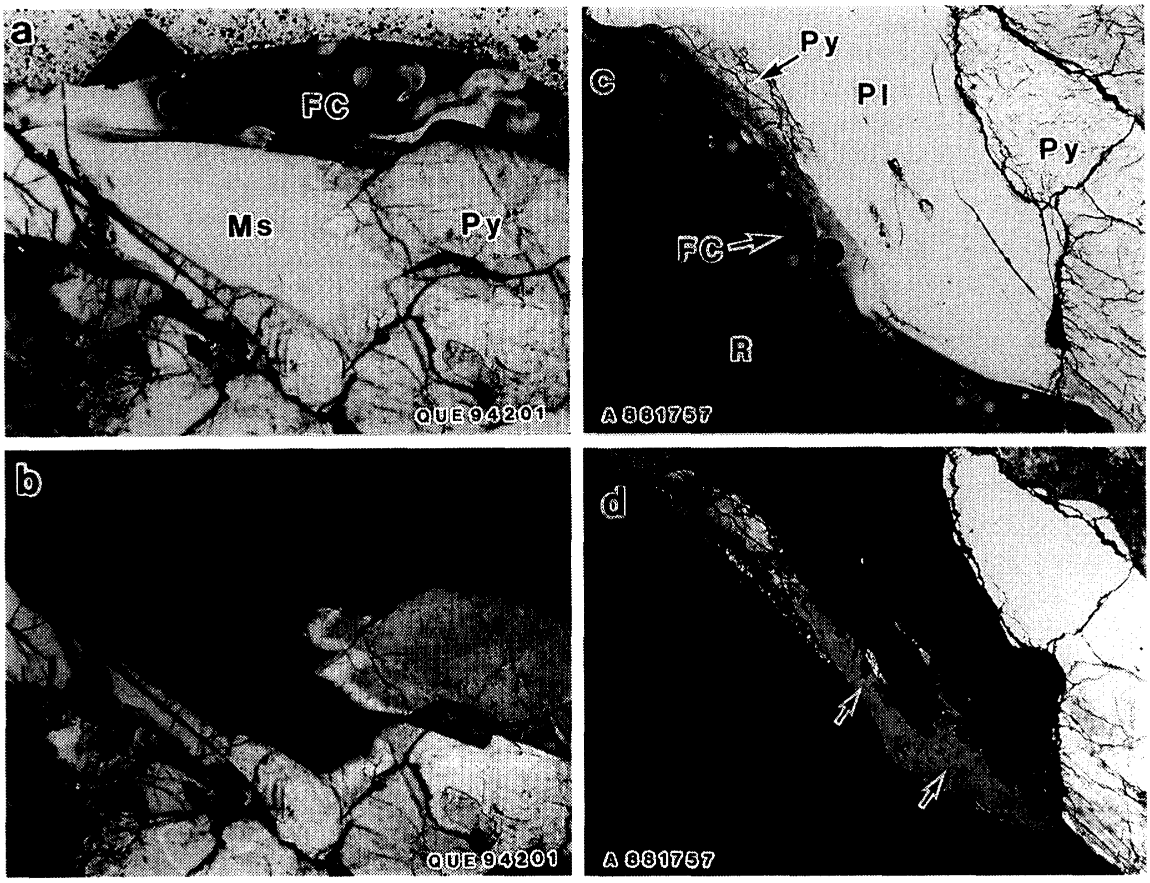

Fig. 6. Optical photomicrographs of QUE94201 Martian meteorite (a, b) and A-881757 lunar meteorite (c, d). (a) and (c): plane-polarized light. (b) and (d): cross-polarized light. The field of view is about 0.6 mm for (a) and (b) and is about 1.2 mm for (c) and (d). Note that QUE94201 "maskelynite" is still amorphous even at the contact to the fusion crust (b).In contrast, A-881757 plagioclase glass converts to crystalline plagioclase (indicated by arrows in d) near the fusion crust. The crystalline area is optically single crystal. Ms: "maskelynite". Py: pyroxene. FC: fusion crust. Pl: plagioclase glass. R: resin.

some isotopic abundances are different from each other (*e.g.*, Fukuoka, 1992; Warren and Kallemeyen, 1993; Torigoye-Kita *et al.*, 1995). These observations suggest that Y-793169 and A-881757 are not co-magmatic. This study further shows that plagioclase in the Y-793169 and A-881757 lunar mare meteorites have different mineralogy possibly due to different shock and thermal histories which they have followed.

Plagioclase in Y-793169 is polycrystalline, indicating a recrystallizing texture. It is noted that their textures are similar to those produced by the annealing experiments of experimentally shocked plagioclase (Ostertag and Stöffler, 1982). They report that recrystallizing plagioclase from shocked plagioclase glass has microlitic polycrystalline textures, but there are clear differences in recrystallizing textures between diaplectic and melt glasses. They suggest that recrystallizing plagioclase grains from a diaplectic glass preserve the initial optical orientations of the original plagioclase grain, but those from a melt glass do not. This is probably because a diaplectic glass is more ordered and preserves the longer range of the relict atomic structure of the original plagioclase grain

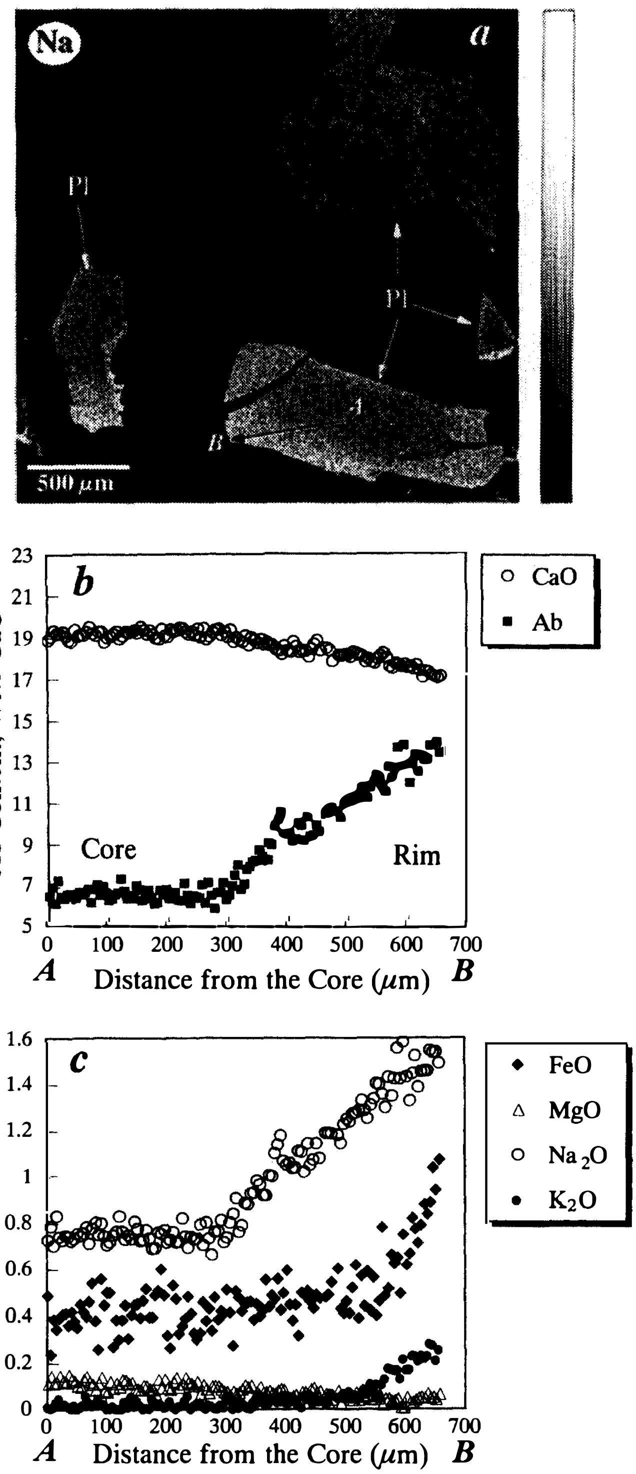

Fig. 7. Na X-ray map (a) and element zoning profiles (b and c) of A-881757 plagioclase glass. (d) shows cation totals along the line. The zoning profiles are obtained from the grain of center bottom of (a). The arrow (A-B) shows a microprobe traverse. Na displays clear zoning in the Na map (a). All elements show systematic chemical zoning from core to rim. Pl: plagioclase glass.

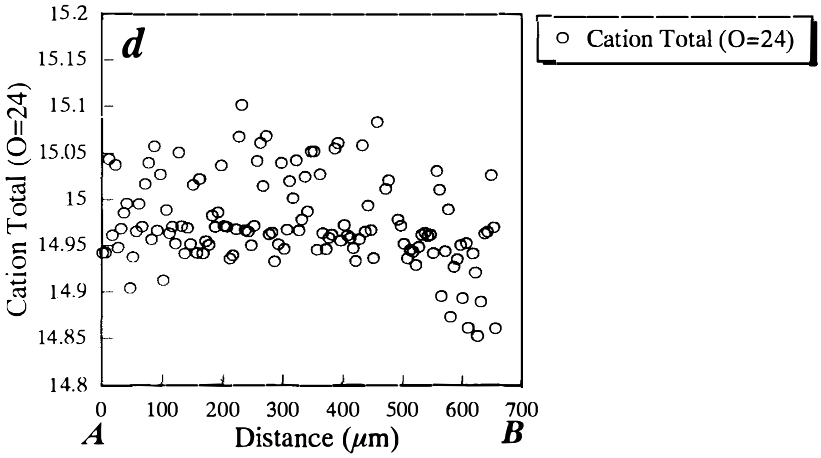

Fig. 7 (continued).

than a melt glass. According to the observation that recrystallizing plagioclase in Y-793169 preserves the original optical orientation, microlitic plagioclase in Y-793169 suggests recrystallization from a diaplectic glass. Although the presence of vesicles within the Y-793169 plagioclase might hint melting, Ostertag and Stöffler (1982) also note that vesicles were formed by thermal annealing of a diaplectic glass even well below the melting point of plagioclase. Mikouchi *et al.* (1998) performed an annealing experiment of maskelynite in the Zagami Martian meteorite and found that completely recrystallizing plagioclase has chemical zoning patterns generally similar to the primary igneous one. They also pointed out that K is one of the most mobile elements during recrystallization due to the presence of grain boundaries of small recrystallizing domains. The K X-ray map of Y-793169 shows that K is distributed along fractures (Fig. 9). This observation is also consistent with recrystallization of plagioclase glass by annealing. Hence, the presence of chemical zoning of Y-793169 plagioclase that is similar to normal igneous zoning is consistent with thermal annealing of shocked plagioclase glass. Therefore, I conclude that plagioclase in Y-793169 experienced slight thermal annealing after the formation of a diaplectic glass by impact. The isotopic study of Y-793169 plagioclase by the K-Ar method suggests disturbance of isotopic system at sometime later than 750 Ma (Torigoye-Kita *et al.*, 1995). This event may correspond to the annealing event which caused recrystallization of plagioclase in Y-793169.

Plagioclase in A-881757 lunar meteorite is a completely isotropic glass unlike Y-793169, but preserves original igneous chemical zoning. This observation is very similar to that of maskelynite in Martian meteorites. Raman spectra of A-881757 plagioclase glass give only broad emissions that are also similar to those of the Martian maskelynite while Y-793169 plagioclase gives clear Raman peaks of plagioclase at 487, 507, and 560 cm^{-1} (Mikouchi *et al.*, 1998). However, maskelynite in Martian meteorites (*e.g.*, QUE94201) does not show recrystallization even at the contact to the fusion crust unlike A-881757 (Fig. 6). This suggests that plagioclase glass in A-881757 preserves more ordered atomic structure of plagioclase than those in Martian meteorites. However, I can not rule out the possibility that maskelynite in Martian meteorites does

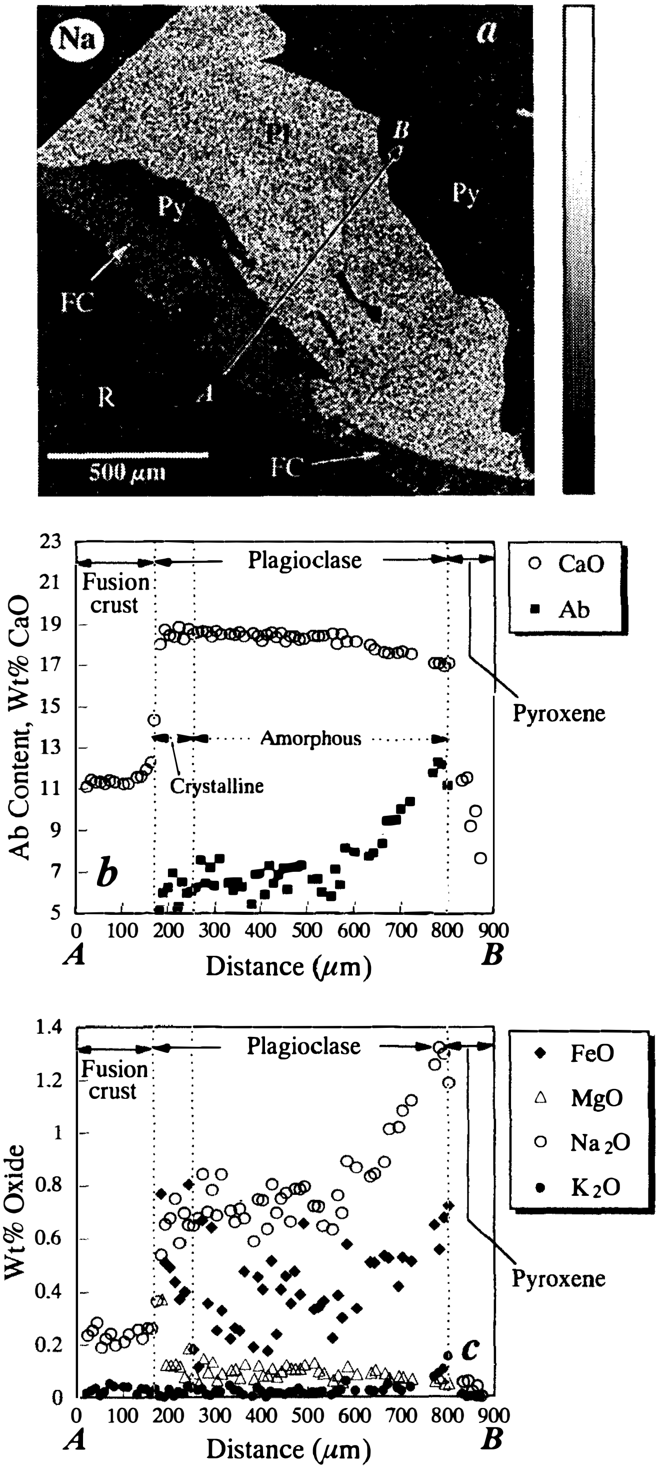

Fig. 8. Na X-ray map (a) and element zoning profiles (b and c) of A-881757 plagioclase glass at the sample edge. The arrow (A-B) in (a) shows a microprobe traverse and the profiles are shown in (b) and (c). There are no compositional gap between the crystalline and amorphous plagioclase (b and c). Pl: plagioclase glass. Py: pyroxene. FC: fusion crust. R: resin.

not convert to crystalline plagioclase because plagioclase in Martian meteorites is more albite-rich (An_{50}) than that in lunar meteorites (An_{90}) (*e.g.*, STÖFFLER and HORNEMANN, 1972). Recrystallizing area of A-881757 plagioclase glass shows a single crystal texture (Fig. 6). This may indicate that shocked plagioclase glass in A-881757 is a diaplectic glass as once shocked plagioclase in Y-793169 was. On the other hand, maskelynite in

Table 2. Chemical composition of Asuka-881757 plagioclase glass.

	Core	Rim
SiO_2	45.35	47.07
TiO_2	0.06	0.02
Al_2O_3	33.84	33.07
FeO	0.56	0.88
MnO	-	0.03
MgO	0.07	0.05
CaO	18.20	17.23
Na_2O	0.98	1.40
K_2O	0.04	0.11
Cr_2O_3	0.04	-
V_2O_3	0.02	0.03
NiO	-	-
P_2O_5	-	-
Total	99.14	99.88
An	*90.91*	*86.63*
Ab	*8.88*	*12.73*
Or	*0.21*	*0.65*
Cation total	15.00	14.98

Martian meteorites is perhaps a melt glass as suggested by El Goresy *et al.* (1997a, b). They pointed out that maskelynite in Shergotty has (1) smooth surface with no cleavage, no contraction cracks and no shock-induced fractures, (2) offshoots of smooth maskelynitic material into fractures after the passage of the shock wave, (3) radiating cracks extensively shattering the neighboring pyroxene and (4) homogeneous chemical composition. Although many of these characteristics are similar to those in shocked plagioclase glass in A-881757, I suppose that shocked plagioclase glass in A-881757 is probably a diaplectic glass because a diaplectic plagioclase glass has very similar textural appearances to a melt plagioclase glass (Yamaguchi, pers. commun., 1998). The isotope study of A-881757 did not detect any recent isotopic disturbance for the K-Ar system (Misawa *et al.,* 1993; Nagao and Miura, 1993) unlike Y-793169, which shows agreement of preservation of a diaplectic plagioclase glass without any slight annealing episodes. Probably the $^{40}Ar/^{39}Ar$ age of 3.8 Ga for plagioclase glass in A-881757 is the formation age of a diaplectic plagioclase glass as is suggested by Misawa *et al.* (1993). K distribution of A-881757 is also different from that of Y-793169. Unlike Y-793169, K is distributed mostly within plagioclase glass and is absent in fractures (Fig. 9). This also suggests that element distribution in A-881757 plagioclase glass has not been affected by annealing.

Both meteorites have very ancient crystallization ages of about 3.8–3.9 Ga that are significantly older than those of LT and VLT mare basalts (3.2–3.4 Ga) (*e.g.,* Nyquist and Shih, 1992; Misawa *et al.,* 1993; Torigoye-Kita *et al.,* 1995). In these ages of Y-793169 and A-881757 crystallization, it is known that the Moon suffered from the late heavy bombardment (*e.g.,* Tera *et al.,* 1974). The Apollo 11 mare basalts have similar

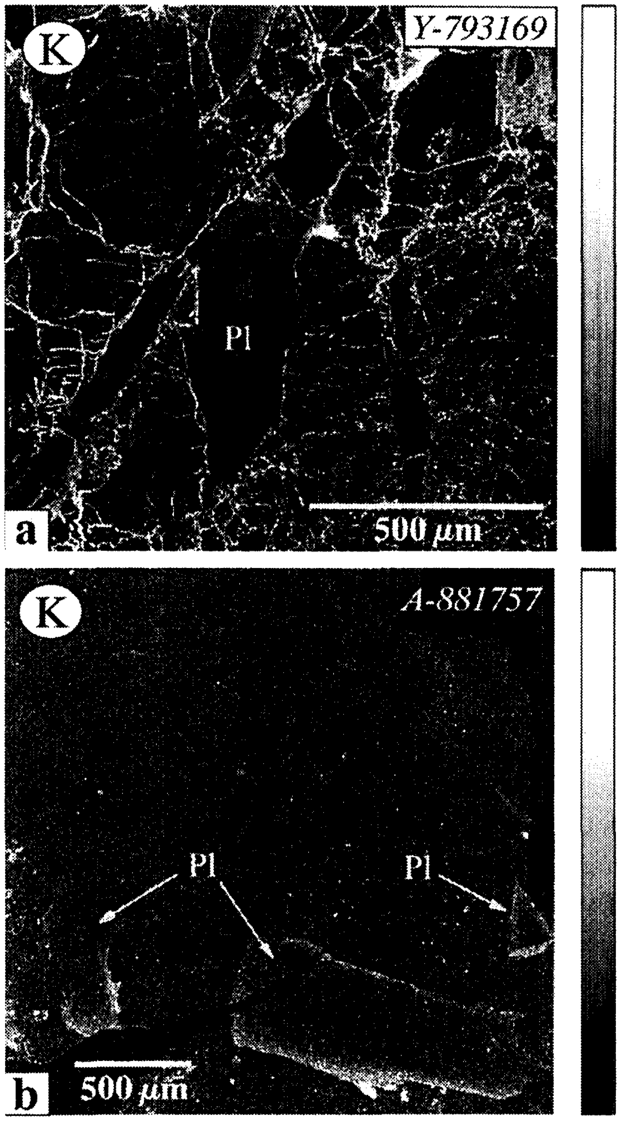

Fig. 9. K X-ray maps of Y-793169 and A-881757 lunar meteorites. (a): Y-793169. (b): A-881757. K is mainly distributed along fractures in Y-793169 (a). In contrast, K is concentrated in plagioclase glass, especially at the rims in A-881757 (b). Pl: plagioclase (glass).

crystallization ages to those of Y-793169 and A-881757 (*e.g.*, TATSUMOTO, 1970) and plagioclase sometimes transformed to a diaplectic glass (*e.g.*, ALBEE and CHODOS, 1970; VON ENGELHARDT *et al.*, 1970). Therefore, the presence of a diaplectic glass in Y-793169 and probably A-881757 is consistent with their ancient crystallization ages (late heavy bombardment) (MISAWA *et al.*, 1993; TORIGOYE-KITA *et al.*, 1995) and shows a similarity to the Apollo 11 mare basalts in shock metamorphism. However, I can not rule out the possibility for A-881757 that a diaplectic glass was formed when it was ejected from the Moon at 1.35 Ma (*e.g.*, NAGAO and MIURA, 1993).

Thus, shocked plagioclase glass in A-881757 is probably a diaplectic glass as several observations suggest in this study. Nevertheless, more detailed study such as an annealing experiment of shocked plagioclase in A-881757 is required to give further confirmation on this conclusion.

5. Conclusions

(1) Y-793169 lunar meteorite contains microlitic polycrystalline plagioclase aggre-

gates that were clearly formed by recrystallization, yet they preserve the overall optical orientation of the original grain. Combining with the presence of small vesicles and chemical zoning from the An-rich core to the An-poor rim, plagioclase in Y-793169 recrystallized from a diaplectic glass by thermal annealing as the K-Ar study of plagioclase suggests isotopic disturbance at sometime later than 750 Ma.

(2) A-881757 plagioclase has completely transformed into an optically isotropic glass similar to maskelynite in Martian meteorites. Both the preservation of systematic chemical zoning and the presence of crystalline plagioclase near the fusion crust suggest that plagioclase glass in A-881757 is a diaplectic glass. Unlike Y-793169, plagioclase glass in A-881757 has not been modified by the later thermal events, which is consistent with the old ^{40}Ar-^{39}Ar age of 3.8 Ga.

(3) The presence of a diaplectic plagioclase glass in Y-793169 (now recrystallized) and A-881757 supports their old crystallization ages (3.8–3.9 Ga) that match the late heavy bombardment of the Moon. Y-793169 and A-881757 also show similarities to ancient mare basalts (like Apollo 11) in shock metamorphism, that is, all of these rocks contain diaplectic plagioclase glasses produced by impact.

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References

ALBEE, A.L. and CHODOS, A.A. (1970): Microprobe investigations on Apollo 11 samples. Proc. Apollo 11 Lunar Sci. Conf., **1**, 135–157.

ARAI, T., TAKEDA, H. and WARREN, P.H. (1996): Four lunar mare meteorites: Crystallization trends of pyroxenes and spinels. Meteorit. Planet. Sci., **31**, 877–892.

BISCHOFF, A. and STÖFFLER, D. (1992): Shock metamorphism as a fundamental process in the evolution of planetary bodies: Information from meteorites. Eur. J. Mineral., **4**, 707–755.

EL GORESY, A., CHEN, M., SHARP, T.G., WOPENKA, B. and WEINBURCH, S. (1997a): Shock-induced high-pressure phase transformations in chondritic and differentiated meteorites: Solid-state transformations, high-pressure liquidus phases, and alkali vapour fractionation. Antarctic Meteorites XXI. Tokyo, Natl Inst. Polar Res., 27–30.

EL GORESY, A., WOPENKA, B., CHEN, M. and KURAT, G. (1997b): The Saga of maskelynite in Shergotty. Meteorit. Planet. Sci., **32**, Suppl., 214A.

FUKUOKA, T. (1992): Geochemistry of lunar meteorites, Asuka-31 and Yamato-793169. Papers Presented to the 17th Symposium on Antarctic Meteorites, Aug. 19–21, 1992. Tokyo, Natl Inst. Polar Res., 251–253.

KOEBERL, C., KURAT, G. and BRANDSTÄTTER, F. (1993): Gabbroic lunar mare meteorites Asuka-881757 (Asuka-31) and Yamato-793169: Geochemical and mineralogical study. Proc. NIPR Symp. Antarct. Meteorites, **6**, 14–34.

MCKAY, D.S., GIBSON, E.K., Jr., THOMAS-KEPRTA, K.L., VALI, H., ROMANEK, C.S., CLEMETT, S.J., CHILLER, X.D.F, MAECHILING, C.R. and ZARE, R.N. (1996): Search for past life on Mars: Possible relic biogenic activity in martian meteorite ALH84001. Science, **273**, 924–930.

MIKOUCHI, T., MIYAMOTO, M. and MCKAY, G. (1997): Crystallization histories of basaltic shergottites as inferred from chemical zoning of pyroxene and maskelynite. Meteorit. Planet. Sci., **32**, Suppl., A92–A93.

MIKOUCHI, T., MIYAMOTO, M. and MCKAY, G.A. (1998): Shocked plagioclase in martian and lunar meteorites: Textures, chemical compositions, Raman spectra, and implications for their post-shock thermal histories. Antarctic Meteorites XXIII. Tokyo, Natl Inst. Polar Res., 77–79.

MISAWA, K., TATSUMOTO, M., DALRYMPLE, G.B. and YANAI, K. (1993): An extremely low U/Pb source in the Moon: U-Th-Pb, Sm-Nd, Rb-Sr, and $^{40}Ar/^{39}Ar$ isotopic systematics and age of lunar meteorite Asuka 881757. Geochim. Cosmochim. Acta, **57**, 4687–4702.

NAGAO, K. and MIURA, Y. (1993): Noble gas and ^{81}Kr-terrestrial age of Asuka-881757 lunar meteorite. Proc. NIPR Symp. Antarct. Meteorites, **6**, 76–87.

NYQUIST, L.E. and SHIH, C.Y. (1992): The isotopic record of lunar volcanism. Geochim. Cosmochim. Acta, **56**, 2213–2234.

OSTERTAG, R. and STÖFFLER, D. (1982): Thermal annealing of experimentally shocked feldspar crystals. Proc. Lunar Planet. Sci. Conf., 13th, Pt. 1, A457–A463 (J. Geophys. Res., **87** Suppl).

OSTERTAG, R. and STÖFFLER, D. (1983): Shock experiments on feldspar crystals. Proc. Lunar Planet. Sci. Conf., 14th, Pt. 1, B364–B376 (J. Geophys. Res., **88** Suppl).

STÖFFLER, D. and HORNEMANN, U. (1972): Quartz and feldspar glasses produced by natural and experimental shock. Meteoritics, **7**, 371–394.

TAKEDA, H., ARAI, T. and SAIKI, K. (1993): Mineralogical studies of lunar meteorite Yamato-793169, a mare basalt. Proc. NIPR Symp. Antarct. Meteorites, **6**, 3–13.

TATSUMOTO, M. (1970): Age of the moon: An isotopic study of U-Th-Pb systematics of Apollo 11 lunar samples-II. Proc. Apollo 11 Lunar Sci. Conf., **2**, 1595–1612.

TERA, F., PAPANASTASSIOU, D.A. and WASSERBURG, G.J. (1974): Isotopic evidence for a terminal lunar catalysm. Earth Planet. Sci. Lett., **10**, 1–21.

TORIGOYE-KITA, N., MISAWA, K., DALRYMPLE, G.B. and TATSUMOTO, M. (1995): Further evidence for a low U/Pb source in the Moon: U-Th-Pb, Sm-Nd, and Ar-Ar isotopic systematics of lunar meteorite Yamato-793169. Geochim. Cosmochim. Acta, **59**, 2621–2632.

VON ENGELHARDT, W., ARNDT, J., MÜLLER, W.F. and STÖFFLER, D. (1970): Shock metamorphism of lunar rocks and origin of the regolith at the Apollo 11 landing site. Proc. Apollo 11 Lunar Sci. Conf., **1**, 363–384.

WARREN, P.H. and KALLEMEYN, G.W. (1993): Geochemical investigation of two lunar mare meteorites: Yamato-793169 and Asuka-881757. Proc. NIPR Symp. Antarct. Meteorites, **6**, 35–57.

YANAI, K. (1991): Gabbroic meteorite Asuka-31: Preliminary examination of a new type of lunar meteorite in the Japanese collection of Antarctic meteorites. Proc. Lunar Planet. Sci., **21**, 317–324.

YANAI, K. and KOJIMA, H. (1991): Varieties of lunar meteorites recovered from Antarctica. Proc. NIPR Symp. Antarct. Meteorites, **4**, 70–90.

ZIPFEL, J., SPETTEL, B., PALME, H., WOLF, D., FRANCHI, I., SEXTON, A.S., PILLINGER, C.T. and BISCHOFF, A. (1998): Dar al Gani 400: Chemistry and petrology of the largest lunar meteorite. Meteorit. Planet. Sci., **33**, Suppl., A171.

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