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Shock-induced melting, recrystallization, and exsolution in plagioclase from the Martian lherzolitic shergottite GRV 99027

Deqiang WANG and Ming CHEN*

Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, 510640 Guangzhou, China
*Corresponding author. E-mail: mchen@gig.ac.cn

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Abstract–Plagioclase in the Martian lherzolitic shergottite Grove Mountains (GRV) 99027 was shocked, melted, and recrystallized. The recrystallized plagioclase contains lamellae of pyroxene, olivine, and minor ilmenite (<1 µm wide). Both the pyroxene and the olivine inclusions enclosed in plagioclase and grains neighboring the plagioclase were partially melted into plagioclase melt pools. The formation of these lamellar inclusions in plagioclase is attributed to exsolution from recrystallizing melt. Distinct from other Martian meteorites, GRV 99027 contains no maskelynite but does contain recrystallized plagioclase. This shows that the meteorite experienced a slower cooling than maskelynite-bearing meteorites. We suggest that the parent rock of GRV 99027 could have been embedded in hot rocks, which facilitated a more protracted cooling history.

INTRODUCTION

Plagioclase is a common rock-forming mineral in stone meteorites. All Martian meteorites display shock-metamorphic features, in which plagioclase is usually transformed to maskelynite, which is an amorphous or glass phase (Stöffler et al. 1986; Jagoutz 1989; Langenhorst et al. 1991; Harvey et al. 1993; Ikeda 1994, 1997; Scott et al. 1997; Chen and El Goresy 2000; Malavergen et al. 2001; Walton and Spray 2003). Although there is some debate regarding the exact nature of this amorphous phase (Chen and El Goresy 2000; Stöffler 2000), all of these studies indicate that the formation of maskelynite is related to the shock-induced transformation of plagioclase. Maskelynite has thus been widely used as an important shock indicator in meteorites, especially shock-induced pressure and temperature (Stöffler et al. 1986; Langenhorst et al. 1991; Scott et al. 1997; Chen and El Goresy 2000; Walton and Spray 2003).

The Grove Mountains (GRV) 99027 meteorite is an lherzolitic shergottite recovered in the Grove Mountains region, Antarctica, by the Sixteenth Chinese Antarctic Research Expedition in 1999–2000. This meteorite is believed to be derived from Mars (Lin et al. 2003; Hsu et al. 2004). Previous studies indicated that plagioclase was transformed or partially transformed to maskelynite (Lin et al. 2003; Hsu et al. 2004). In this paper, we report the new interpretation of the so-called "maskelynite." Our results indicate that previously reported "maskelynite" is not an amorphous phase, but rather crystalline plagioclase. The plagioclase in the meteorite experienced shock-induced melting, recrystallization, and exsolution. The existence of recrystallized plagioclase in the GRV 99027 meteorite may suggest a distinct cooling history from maskelynite-bearing Martian meteorites.

SAMPLES AND METHODS

Petrographical observations on polished thin sections of the GRV 99027 meteorite were conducted using an optical microscope and a Hitachi S-3500N scanning electron microscope equipped with a Link ISIS 300 X-ray energy dispersive spectrometer (EDS). The quantitative chemical analysis of various phases was conducted using a JEOL JXA-8100 electron microprobe at 15 kV accelerating voltage and 10 nA beam current. Raman spectra were recorded with a Renishaw RM-2000 instrument. A microscope was used to focus the excitation beam (Ar^+ laser, 514 nm line) to a 2 µm spot and to collect the Raman signal. Signal accumulations lasted for 300 s. All equipment is housed at the Guangzhou Institute of Geochemistry, Chinese Academy of Science.

RESULTS

The meteorite sample contains two distinct assemblages comprising poikilitic and non-poikilitic areas (Fig. 1). Poikilitic areas consist of millimeter-size pyroxene (pigeonite) oikocrystals ($En_{66–77}Fs_{20–23}Wo_{3–14}$) enclosing olivine ($Fa_{27}$), chromite, and ilmenite as inclusions. The non-

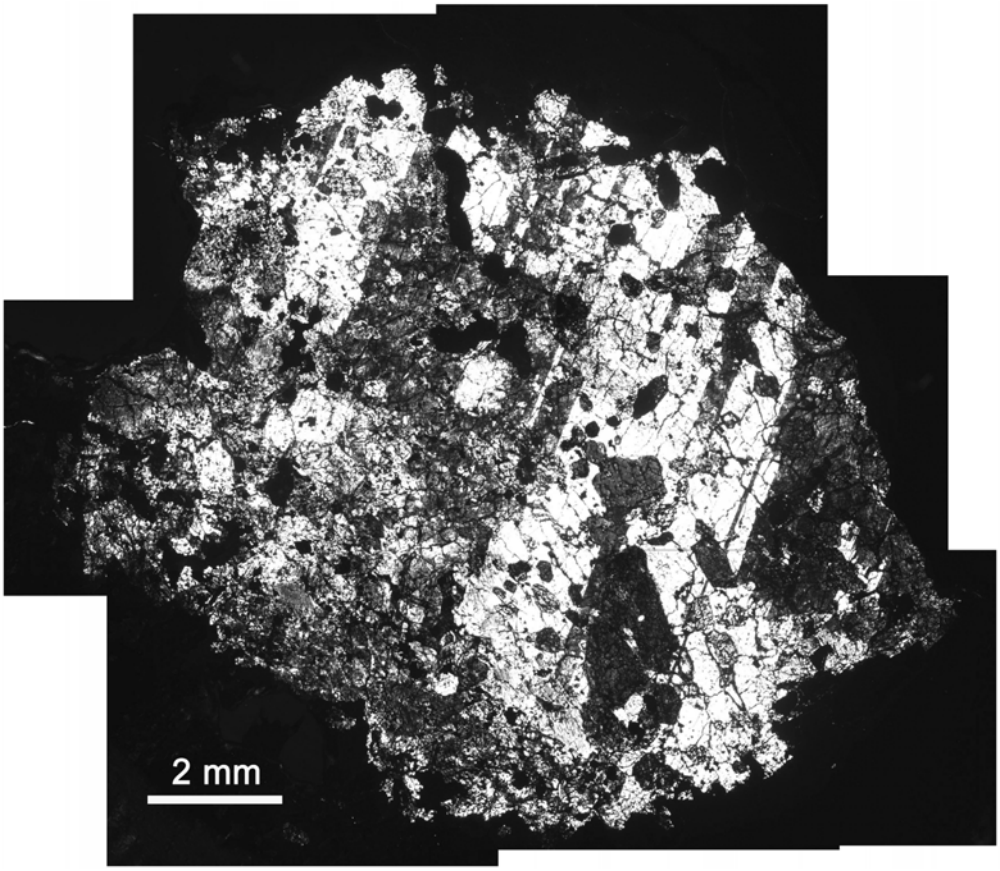

Fig. 1. Transmitted light photograph of the GRV 99027 thin section showing poikilitic (right side) and non-poikilitic areas. Crossed polarizers.

poikilitic areas are composed of olivine ($Fa_{27–30}$), pigeonite ($En_{66–70}Fs_{24–27}Wo_{7–16}$), and augite ($En_{49–53}Fs_{14–15}Wo_{32–38}$) with interstitial plagioclase, and accessory chromite, ilmenite, and whitlockite (Lin et al. 2003; Hsu et al. 2004). Grain sizes of minerals in the non-poikilitic area are mostly 50–500 µm. Pigeonite both from poikilitic and non-poikilitic areas locally contains exsolution lamellae of augite and shock-induced mechanical polysynthetic twinning lamellae.

Silicate melt pockets up to 1 mm across were observed in the non-poikilitic areas (Fig. 2). These melt pockets consist of a fine-grained polymineralic assemblage of olivine, pyroxene, and a small amount of plagioclase. The olivine and pyroxene occur as lath-like grains 5–20 µm in width and 20–200 µm in length. Plagioclase occurs in the interstices of pyroxene and olivine.

The meteorite contains about 12% by volume of plagioclase. These plagioclases have a grain size up to several hundred micrometers (Fig. 3), and display optically anisotropic features and a reduced birefringence in comparison to normal plagioclase (Fig. 4). Optical observation indicates that plagioclase is commonly composed of elongate grains with slight distortion in crystallographic orientation one to the other. Grains are separated by {010} cleavages. Raman spectroscopic analyses indicate that all plagioclase grains are crystalline. No glass phase was identified. Raman spectra of plagioclase display strong bands at 482 and 510 cm^{-1} (Fig. 5). Electron microprobe analyses show that the plagioclase has an average composition of $An_{61}Ab_{32}Or_1$ (Table 1). Some plagioclase grains locally contain irregular Na-rich speckles. Chemical zoning was not found in these plagioclases.

Many plagioclase grains contain olivine and pyroxene inclusions (Fig. 6). Both the olivine and pyroxene that are enclosed in plagioclase and neighbor the plagioclase tend to show irregular shapes but rounded outlines. The rounded outline of pyroxene and olivine is indicative of partial melting. Many plagioclase grains contain branches intruding irregular fractures in the neighboring pyroxene or olivine (Figs. 6 and 8).

Olivine and pyroxene grains in contact with plagioclase grains are locally transformed from large crystals into fine-grained polycrystalline aggregates, which may be up to 140 µm in width (Fig. 3).

Oriented lamellar inclusions from 0.1 to 0.2 µm in width and 1 to 10 µm in length were identified in many plagioclase grains (Figs. 6 and 7). These lamellar inclusions occur as continuous or discontinuous rows distributed along the {010} cleavages of plagioclase (Fig. 4). EDS analyses reveal that

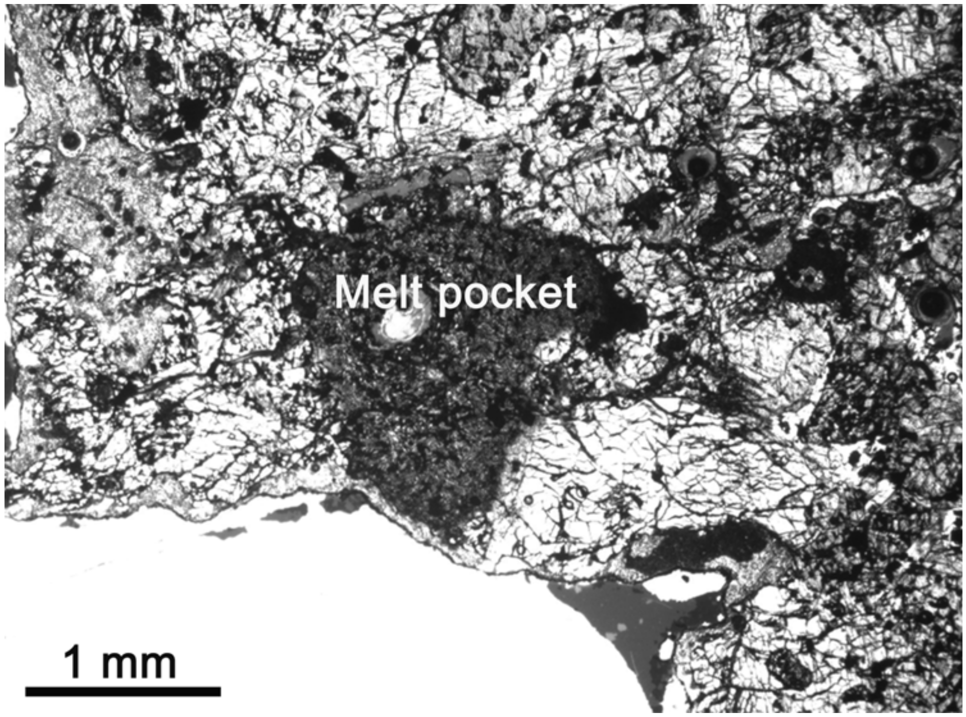

Fig. 2. A recrystallized polymineralic melt pocket in the non-poikilitic areas. Plane-polarized light.

predominant lamellae are low-Ca pyroxene with small amounts of olivine and minor ilmenite (Table 1). Raman spectroscopic analyses also prove that these lamellae are pyroxene, olivine, and ilmenite, respectively, in which the Raman bands at 1004, 674, 660, and 328 cm^{-1} correspond to pyroxene, those at 850 and 822 cm^{-1} to olivine, and those at 688, 376, and 231 cm^{-1} to ilmenite, in addition to the Raman bands from plagioclase at 482 and 510 cm^{-1} (Fig. 9). Bulk analysis of plagioclase grains containing lamellar inclusions shows a composition of plagioclase with slightly enriched FeO, MgO, and TiO_2, which suggests a mixed composition from plagioclase and small amount of pyroxene, olivine, and ilmenite (Table 1). The abundance of lamellar inclusions in plagioclase varies from grain to grain.

DISCUSSION AND CONCLUSIONS

Maskelynite has been found in many shocked meteorites. Recent studies indicate that maskelynite is not a diaplectic glass, but rather a glass derived from melted plagioclase (Scott et al. 1997; Chen and El Goresy 2000). In fact, the shock-induced transformation of plagioclase includes the formation of diaplectic glass, glass melt, maskelynite, and the high-pressure polymorph hollandite. The transformation of diaplectic plagioclase glass takes place at lower pressure (20–40 GPa) than melting (>40 GPa) (Milton and Decarli 1963; Gibbons and Ahrens 1977). The transformation of plagioclase to maskelynite corresponds to an equilibrium shock pressure and temperature below 45 GPa and 1000 °C (Stöffler et al. 1986, 1991; Scott et al. 1997; Langenhorst and Poirier 2000). The formation of maskelynite and hollandite requires not only higher pressure but also a longer duration of high pressure, whereas plagioclase melt is produced after decompression (Chen and El Goresy 2000). It appears that maskelynite is quenched under pressure, whereas the crystallization of plagioclase melt requires slow cooling after decompression. Usually, crystalline plagioclase derived from shock-induced plagioclase melt is seldom found in meteorites. In contrast to other Martian meteorites that contain maskelynite (Stöffler et al. 1986; Langenhorst et al. 1991; Harvey et al. 1993; Ikeda 1997; Scott et al. 1997; Chen and El Goresy 2000; Malavergen et al. 2001), the shocked plagioclase in the GRV 99027 meteorite was not transformed to maskelynite, but rather occurs as recrystallized phase.

In contrast to olivine and pyroxene, the shock-induced melting of plagioclase can take place at relatively low pressure. It has been observed that both pyroxene and olivine in some Martian meteorites display lower degrees of deformation, such as mosaicism, whereas in plagioclase pervasive melting takes place (Scott et al. 1997; Sharp et al. 1999; Chen and El Goresy 2000). In the GRV 99027 meteorite, plagioclase branches intruding on irregular fractures of neighboring pyroxene or olivine, demonstrating the formation of liquid plagioclase melt during shock event (Figs. 6 and 8). These branches were formed by the injection of a plagioclase melt into fractures in the neighboring silicates. The rounded outlines of pyroxene and olivine that occur either as inclusions in plagioclase or neighboring grains

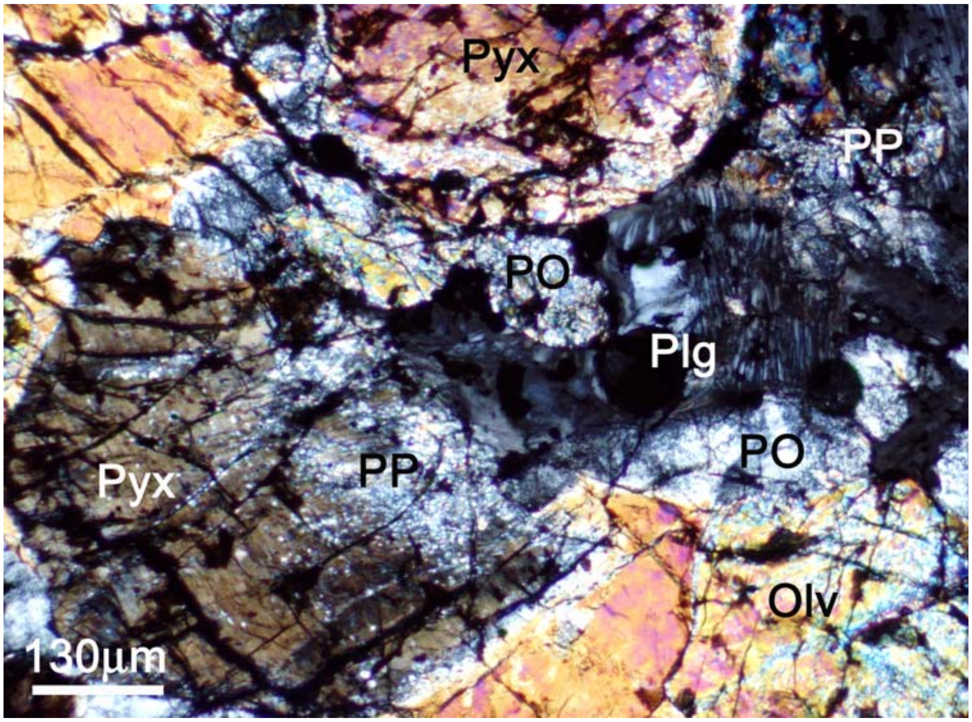

Fig. 3. A plagioclase grain occurring in the interstice of olivine and pyroxene in the non-poikilitic area. Note that olivine and pyroxene (pigeonite) change from large crystal to polycrystalline aggregates in contact with plagioclase. The plagioclase displays heterogeneous optical extinction showing polycrystalline nature. Pyx = pyroxene; Olv = olivine; Plg = plagioclase; PP = polycrystalline pyroxene; PO = polycrystalline olivine. Crossed polarizers.

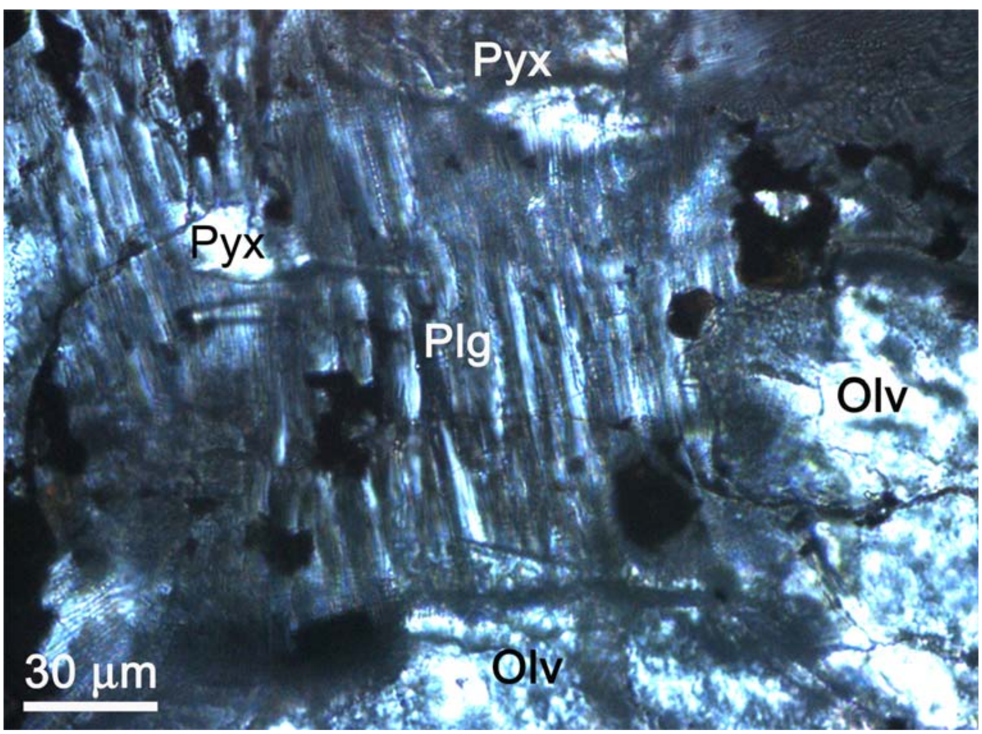

Fig. 4. A plagioclase grain displaying anisotropic optical property in polarized light with reduced birefringence. The plagioclase crystal is subdivided into slices with slight distortion in crystallographic orientation one to the other. The slices are separated by {010} cleavages and lamellar inclusions. Pyx = pyroxene; Olv = olivine; Plg = plagioclase. Crossed polarizers.

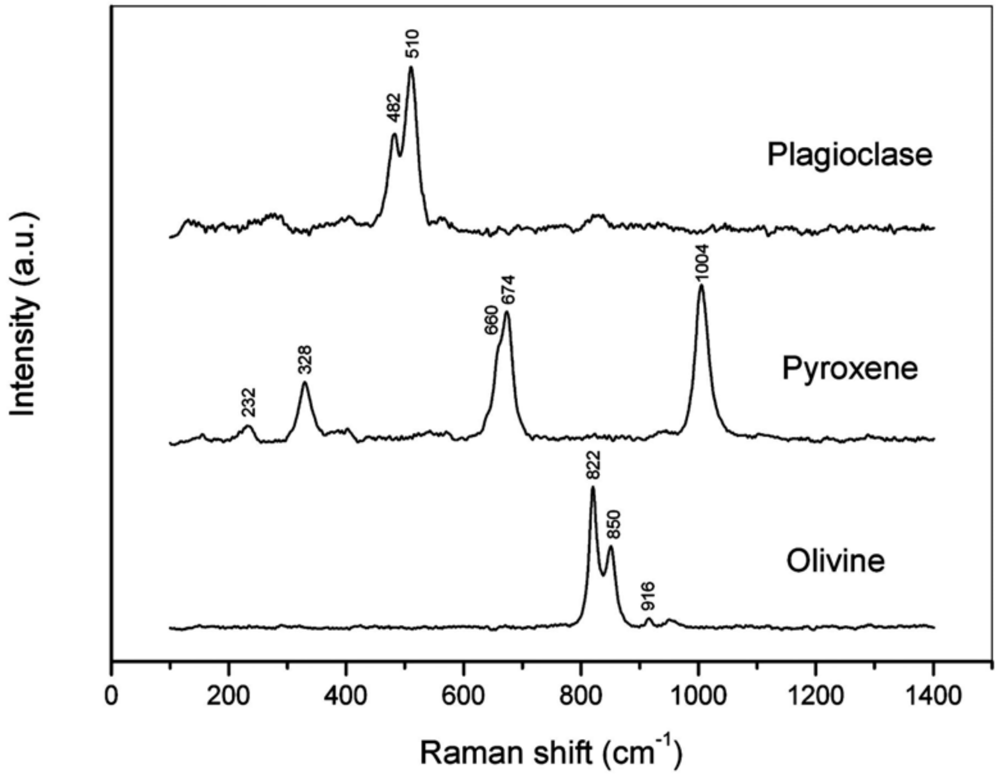

Fig. 5. Raman spectra of plagioclase, pyroxene, and olivine in the host meteorite.

Table 1. Chemical compositions (wt%) of minerals.

	Plag[a]	Bulk[b, c]	Ex-Pyx[b]	Ex-Olv[b]	Ex-Ilm[b]	Olv[a]	Pig[a]	Aug[a]
SiO_2	55.80	52.96	54.33	38.76	0.60	38.49	55.24	53.13
Al_2O_3	28.04	22.14	0.99	–	0.63	–	0.66	2.18
TiO_2	0.05	2.56	0.45	–	52.61	–	0.12	0.45
MnO	0.03	0.06	0.60	0.47	0.76	0.43	0.37	0.31
FeO	0.30	2.82	15.28	23.84	36.76	23.93	13.44	8.45
MgO	0.05	2.92	24.13	36.82	7.42	37.10	25.81	17.33
CaO	9.71	11.16	3.84	0.10	0.22	0.20	2.46	16.26
Na_2O	5.37	4.27	0.05	–	0.10	–	0.10	0.25
K_2O	0.18	0.15	–	–	–	–	–	0.03
Cr_2O_3	–	0.03	0.33	–	0.90	–	0.45	0.80
P_2O_5	0.26	0.93	–	–	–	–	0.15	0.22
Total	99.79	100	100	100	100	100.15	98.80	99.41

[a]Analyses by electron microprobe.
[b]Analyses by EDS.
[c]Bulk composition from an area of plagioclase containing both plagioclase and exsolved silicates.
Plag = plagioclase; Pyx = pyroxene; Olv = olivine; Pig = pigeonite; Aug = augite; Ilm = ilmenite; Ex = exsolution.

in contact with plagioclase suggest that both pyroxene and olivine in contact with the plagioclase melt were partially melted (Fig. 6). Because of the melting of pyroxene and olivine, the shock temperature in the plagioclase melt was estimated to be above 1500 °C (Stöffler et al. 1991).

Polycrystalline zones of pyroxene and olivine surrounding plagioclase grains are indicative of shock-induced high temperatures around the plagioclase melt pool (Fig. 3). The high temperature in the plagioclase melt could result in local melting and recrystallization of both pyroxene and olivine. Similar polycrystalline aggregates of pyroxene and olivine can be found only in other heavily shock-metamorphosed meteorites showing melting and recrystallization in silicates (Chen and Xie 1996). It is clear that these polycrystalline zones of pyroxene and olivine would not be produced if pyroxene, olivine, and plagioclase in the GRV 99027 meteorite were crystallized from a normal magmatic sequence.

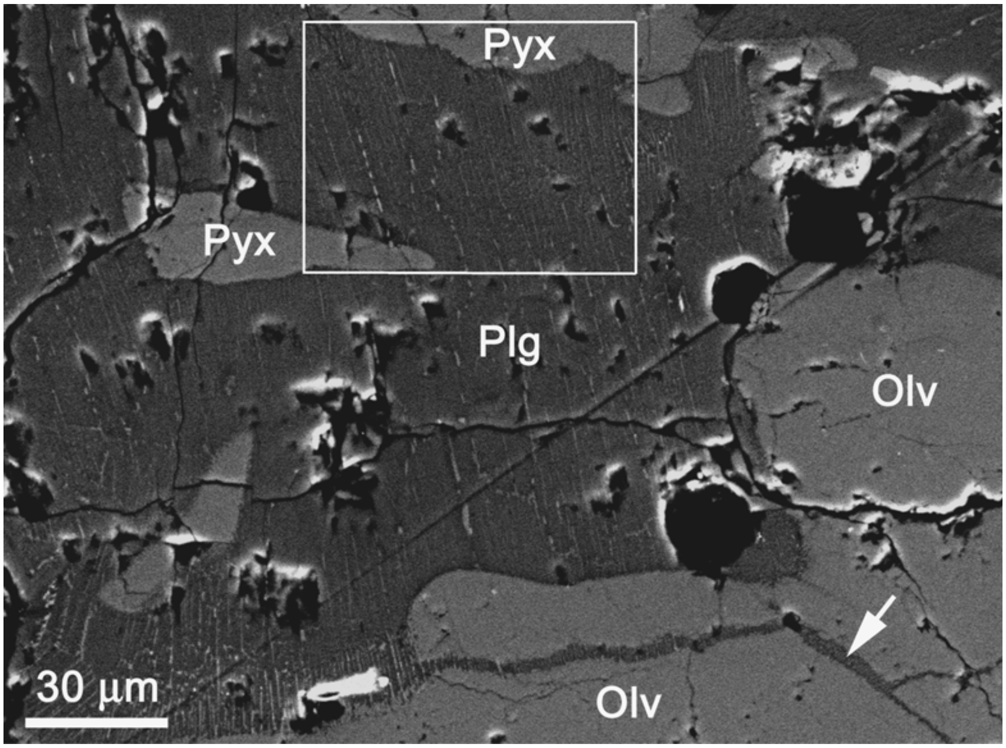

Fig. 6. A backscattered electron image of a plagioclase grain showing pyroxene inclusions and oriented lamellae. The arrow indicated a plagioclase branch intruding fractures of the neighboring olivine. Note the irregular shapes and rounded outlines in pyroxene and olivine occurring as inclusions inside the plagioclase and wall minerals surrounding plagioclase. Pyx = pyroxene; Olv = olivine; Plg = plagioclase.

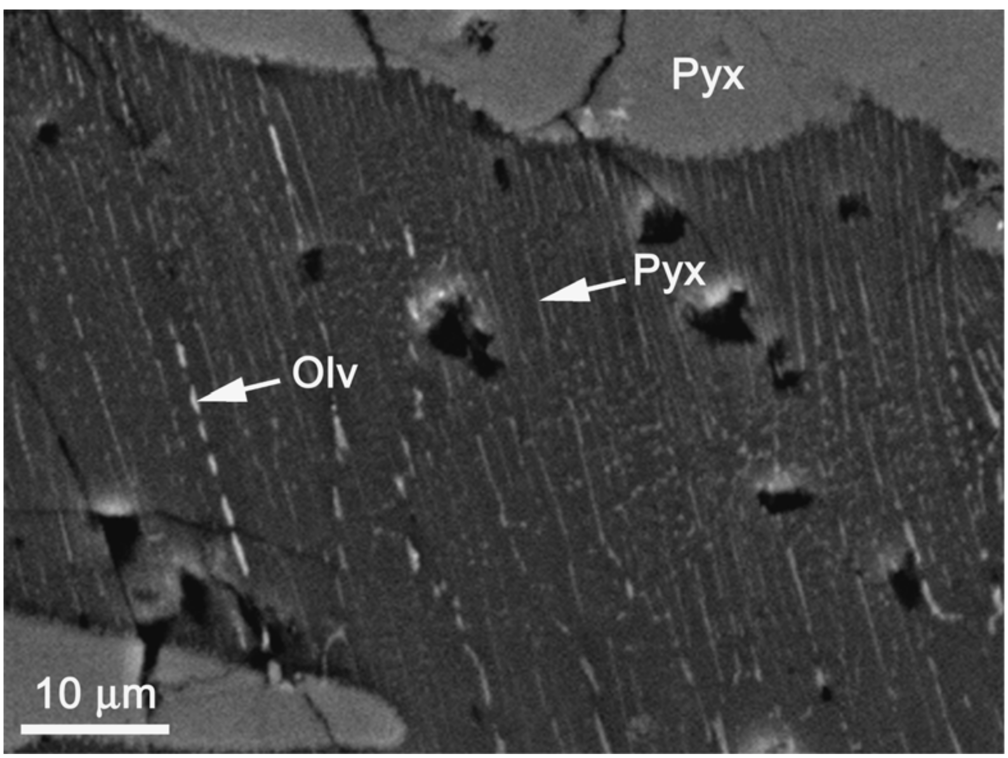

Fig. 7. A high-magnification image showing well-oriented lamellae in plagioclase. These lamellae are mainly pyroxene with small amounts of olivine and ilmenite. Pyx = pyroxene; Olv = olivine; Plg = plagioclase.

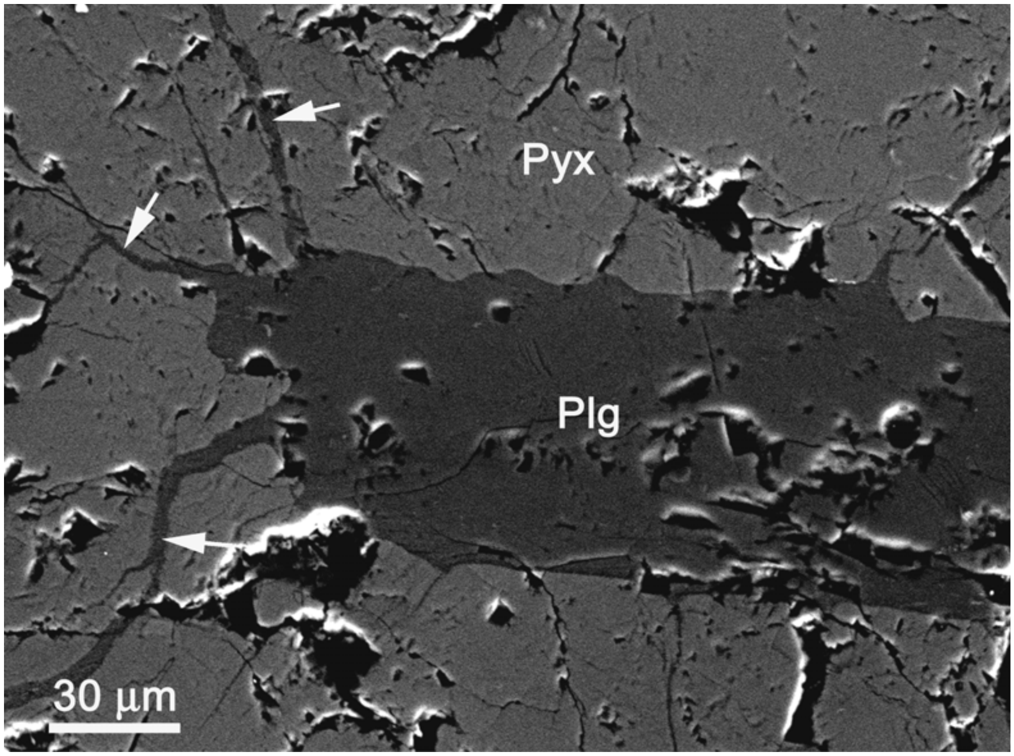

Fig. 8. A backscattered electron image of plagioclase showing branches (arrows) intruding into irregular fractures of the neighboring pyroxene. Pyx = pyroxene; Plg = plagioclase.

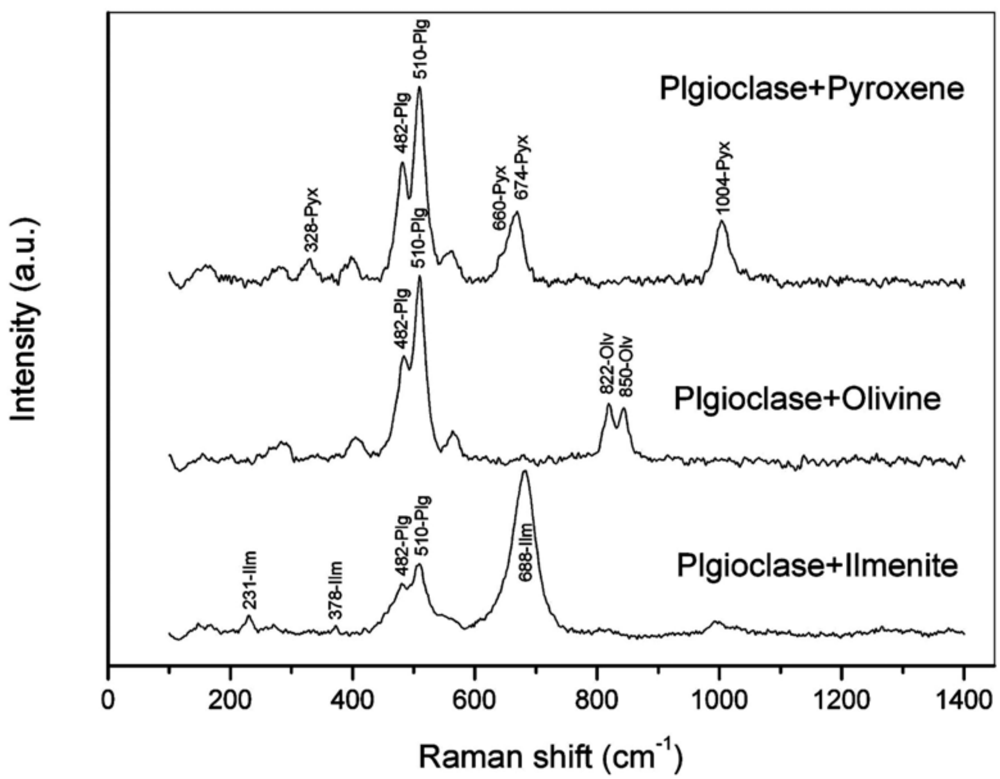

Fig. 9. Raman spectra showing that the plagioclase contains lamellae of pyroxene, olivine, and ilmenite. Pyx = pyroxene; Olv = olivine; Plg = plagioclase.

It is therefore reasonable to estimate that previous plagioclase in the GRV 99027 meteorite was shock-heated to a temperature that caused melting of both pyroxene and olivine. At such a high temperature, all plagioclase was melted, whereas pyroxene, olivine, and ilmenite were locally dissolved into the plagioclase melt. A plagioclase solid solution with incorporated components from dissolved minerals was therefore produced.

Exsolution of minerals with different compositions and structures has been reported in many terrestrial rocks, especially metamorphosed mantle rocks. It was reported that olivine from peridotite exsolves ilmenite inclusions because of the formation of β- or γ-phase solid solution at high pressure and temperature (Dobrzhineskaya et al. 1996). Garnet in eclogite contains exsolution inclusions of clinopyroxene, rutile, and apatite, which is due to a pyroxene solid solution at high pressure and temperature (Ye et al. 2000). Exsolution of amphibole was also found in plagioclase in terrestrial rocks due to thermal metamorphism (Smith and Steele 1974).

The exsolution of augite and ilmenite have been reported in plagioclase from a harzburgite of lunar rocks (Norde 1976; Warren et al 1990). Here we explain that the oriented lamellar inclusions in plagioclase in the GRV 99027 meteorite were formed because of exsolution. The shock-induced melting of plagioclase at high temperature plays a key role in forming a plagioclase solid solution such that it accommodates other elements from dissolved pyroxene, olivine, and ilmenite. Upon cooling, the solid solution separates into distinct crystalline phases including pyroxene, olivine, and ilmenite along {010} planes of plagioclase. These oriented lamellar inclusions in the plagioclase of the GRV 99027 meteorite could not be a mesostasis solidified from immiscible multiphase liquids. The distribution of phases in the mesostasis is random and there should be no crystallographic relation among phases (Chen and El Goresy 2000). The oriented lamellar inclusions in the GRV 99027 meteorite could not be produced through solidification of immiscible multiphase liquids.

The absence of maskelynite in the GRV 99027 indicates that the plagioclase melt crystallized at a slow cooling rate after decompression. The slow cooling in the meteorite is also supported by the totally crystallized silicate melt pockets in the non-poikilitic areas, because the rapid cooling of silicate melt pockets in meteorites generates cryptocrystalline to glassy silicate masses (Dodd and Jarosewich 1979). The slow cooling of GRV 99027 plays a key role in the recrystallization and exsolution in the plagioclase melt. GRV 99027 is the first Martian meteorite in which shock-induced plagioclase melt has recrystallized as plagioclase. It is also the first documented occurrence of mineral exsolution in plagioclase in Martian samples. We propose that the parent rock of GRV 99027 could have been embedded in relatively hot rocks in order to facilitate slow cooling.

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