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A shock-produced (Mg, Fe)SiO_3 glass in the Suizhou meteorite

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Abstract–Ovoid grains consisting of glass of stoichiometric (Mg, Fe)SiO_3 composition that is intimately associated with majorite were identified in the shock veins of the Suizhou meteorite. The glass is surrounded by a thick rim of polycrystalline majorite and is identical in composition to the parental low-Ca pyroxene and majorite. These ovoid grains are surrounded by a fine-grained matrix composed of majorite-pyrope garnet, ringwoodite, magnesiowüstite, metal, and troilite. This study strongly suggests that some precursor pyroxene grains inside the shock veins were transformed to perovskite within the pyroxene due to a relatively low temperature, while at the rim region pyroxene grains transformed to majorite due to a higher temperature. After pressure release, perovskite vitrified at post-shock temperature. The existence of vitrified perovskite indicates that the peak pressure in the shock veins exceeds 23 GPa. The post-shock temperature in the meteorite could have been above 477 °C. This study indicates that the occurrence of high-pressure minerals in the shock veins could not be used as a ubiquitous criterion for evaluating the shock stage of meteorites.

INTRODUCTION

Pyroxene (Mg, Fe)SiO_3 is a major rock-forming mineral in the upper mantle of Earth and in stone meteorites. At high-pressure and temperature, pyroxene transforms to high-pressure polymorphs including majorite, ilmenite, and perovskite. High-pressure polymorphs are considered to be among the major constituents of the Earth's deep mantle (Liu 1974, 1975, 1976, 1980). These high-pressure polymorphs have been found in the shock veins of chondrites (Smith and Mason 1970; Price et al. 1979; Langenhorst et al. 1995; Chen et al. 1996; Sharp et al. 1997; Tomioka and Fujino 1997), but not in terrestrial rocks. Majorite frequently occurs in those strongly shocked meteorites. However, perovskite was not widely identified in these meteorites. Up to now, only two meteorites were reported to contain very small amounts of "perovskite." Tomioka and Fujino (1997) found that crystalline perovskite transformed from orthopyroxene in the Tenham meteorite. Sharp et al. (1997) found vitrified perovskite in the shock veins of the Acfer 040 meteorite, which was interpreted as an amorphized perovskite during pressure release. The natural occurrence of perovskite is not only important for clarifying the phase transformations of pyroxene and the history of pressure and temperature in shocked meteorites, but also for understanding the phase transformation processes in the Earth's mantle.

In addition to high-pressure polymorphs, pyroxene may also be transformed to amorphous phase or glass at shock-produced high pressure and temperature. Pyroxene glass has been reported in some shocked meteorites. Price et al. (1979) reported on the transmission electron microscopy (TEM) observations of a small amount of retrograde glass thought to have inverted from majorite in the shock veins of the Tenham meteorite. In addition, nanometer-sized pyroxene glass was reported to occur at the rim region of crystalline pyroxene in the Allan Hills (ALH) 84001 meteorite as a result of incipient shock melting (Bell et al. 1999). Malavergne et al. (2001) reported Si-Al-rich glass and augite glass in shocked martian meteorites. Recently, Tomioka and Kimura (2003) reported a shock-produced mixture of fine-grained majorite and $CaSiO_3$-rich glass transformed from diopside in an H chondrite.

In comparison to previously found perovskite, vitrified perovskite, and pyroxene glass, here we report a unique occurrence of fine-grained multi-granular (Mg, Fe)SiO_3 glass that intimately coexisted with majorite in the shock veins of the Suizhou meteorite. We found large (Mg, Fe)SiO_3 glass grains that appear to represent the most extensive pyroxene-perovskite transformation observed in meteorites.

Analytical Procedures

Polished thin sections were prepared from the shock-vein-bearing fragments of the Suizhou meteorite. A Hitachi

S-3500N scanning electron microscope equipped with a Link ISIS 300 X-ray energy dispersive spectrometer at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, was employed for detailed mineral and textural investigations in backscattered electron mode.

The quantitative chemical analyses of various phases were made with a JXA-8900RL electron microprobe at 15 kV accelerating voltage and 10 nA sample current at Mainz University (Germany).

Raman spectra of minerals and other solid-state phases were recorded with a Renishaw RM-2000 instrument at the Guangzhou Institute of Geochemistry (China). 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. Accumulations lasting for 300 sec were made. The laser power on the samples was limited to <1–2 mW to avoid deterioration of the samples due to laser heating.

RESULTS

Petrography of the Suizhou Meteorite

The Suizhou meteorite fell in Hubei, China in 1986. A total of 270 kg of the meteorite was recovered. This meteorite was classified as an L6 chondrite and contains a few very thin shock veins (Wang and Li 1990). Petrographic investigations indicated that this meteorite was moderately shock-metamorphosed and classified as shock stage 3–4 (Xie et al. 2001, 2003; Chen et al. 2003).

The meteorite consists of olivine, pyroxene (mainly low-Ca pyroxene and small amount of Ca-pyroxene), plagioclase, kamacite, taenite, troilite, and accessory minerals (chromite, whitlockite, and apatite) (Xie et al. 2001). Most of these minerals have intact structures, except for plagioclase. Olivine and pyroxene display a weak mosaic texture and usually contain abundant regular fractures and 3 to 4 sets of planar fractures (Fig. 1). Optically, the undulatory extinction is very weak for most olivine and pyroxene grains. About 30% of the plagioclase grains have normal optical properties which indicate that its crystal structure remains intact (Figs. 2a and 2b). Most of the remaining plagioclase grains have a reduced birefringence and contain abundant planar deformation features (PDFs), and some grains display a partially isotropic nature (Figs. 2c and 2d). Only the plagioclase grains that are close to the shock veins (at a distance of <300–400 μm) were transformed to maskelynite, a melted plagioclase glass (Figs. 2e and 2f).

The shock veins were very poorly developed in the meteorite. We examined all fragments of the meteorite and only found a few very thin black veins of chondritic

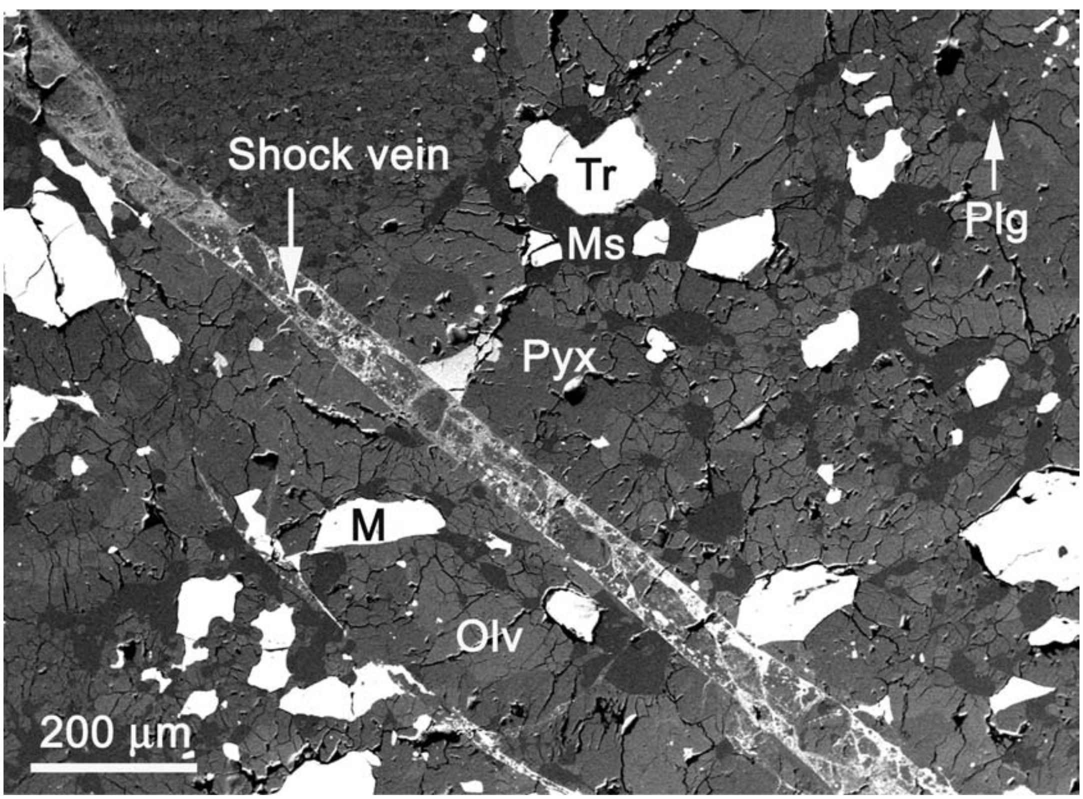

Fig. 1. A backscattered electron (BSE) image showing a shock vein intersecting the chondritic portion of the Suizhou meteorite. Note that the olivine (Olv), pyroxene (Pyx), and plagioclase (Plg) contain abundant fractures, while maskelynite (Ms) displays little fracturing in the interior; M = Fe-Ni metal; Tr = troilite.

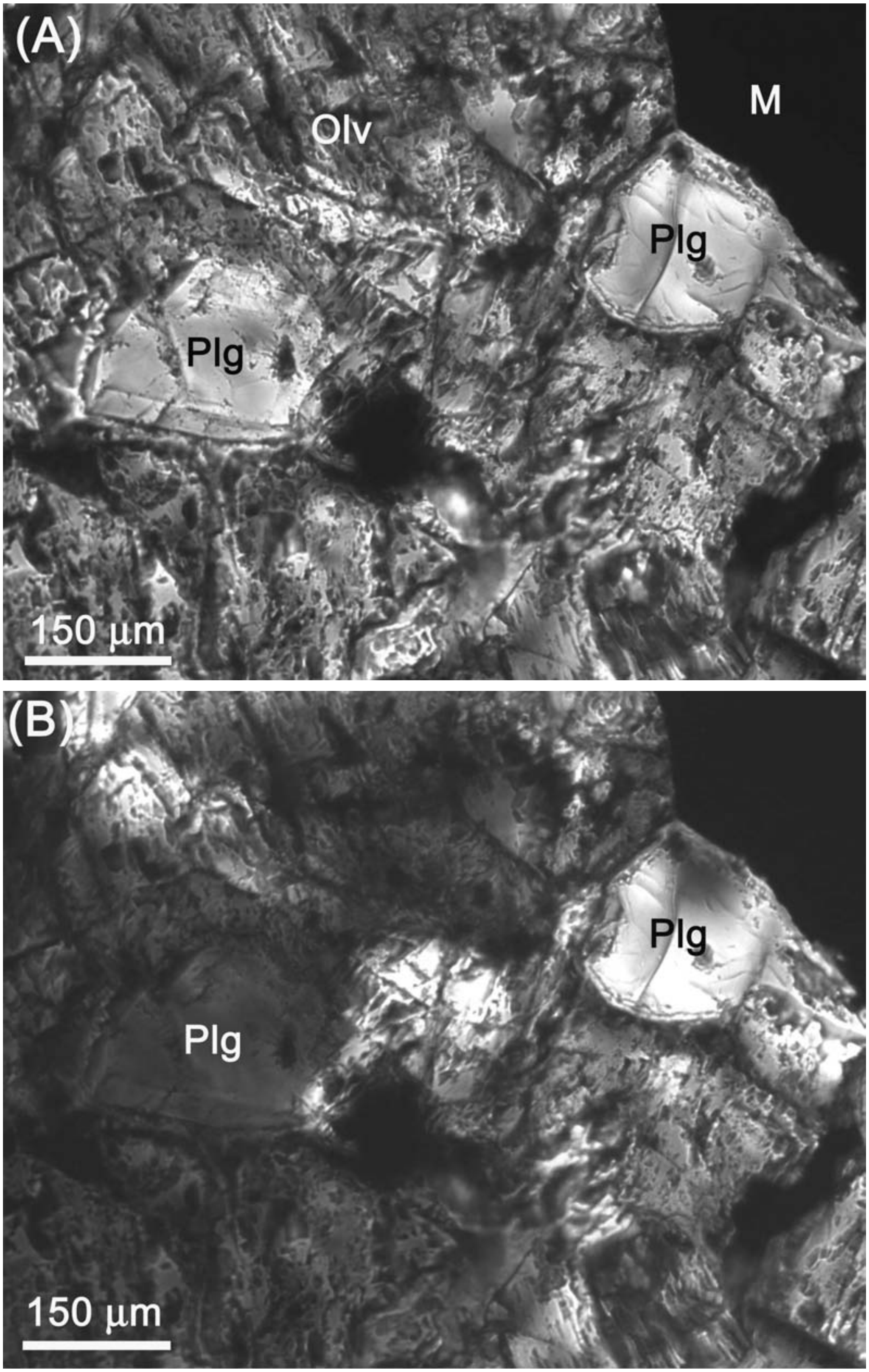

Fig. 2. Transmitted light images of a chondritic portion of the Suizhou meteorite: a) a plane polarized image showing the occurrence of plagioclase. Note that these plagioclases are cut by many cracks; b) a crossed polarized image of the same area in (a) showing crystalline plagioclase; Plg = plagioclase; Olv = olivine; M = Fe-Ni metal.

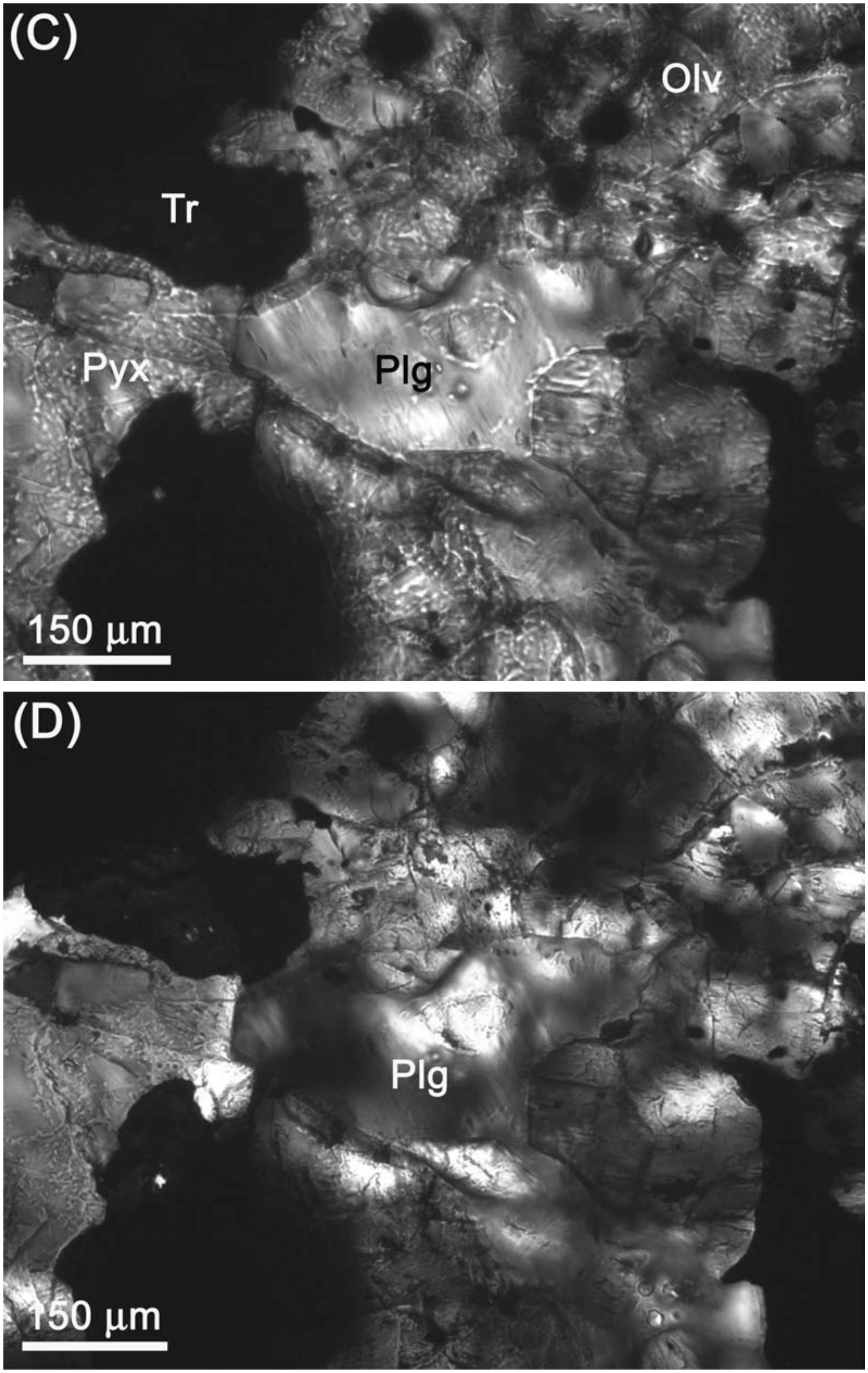

Fig. 2. *Continued.* Transmitted light images of a chondritic portion of the Suizhou meteorite: c) a plane polarized image showing plagioclase with abundant planar deformation features (PDFs); d) a crossed polarized image of the same area in (c) in which lamella-like PDFs can be clearly recognized. This grain has a reduced birefringence and contains locally isotropic area; Plg = plagioclase; Olv = olivine; Pyx = pyroxene; Tr = troilite.

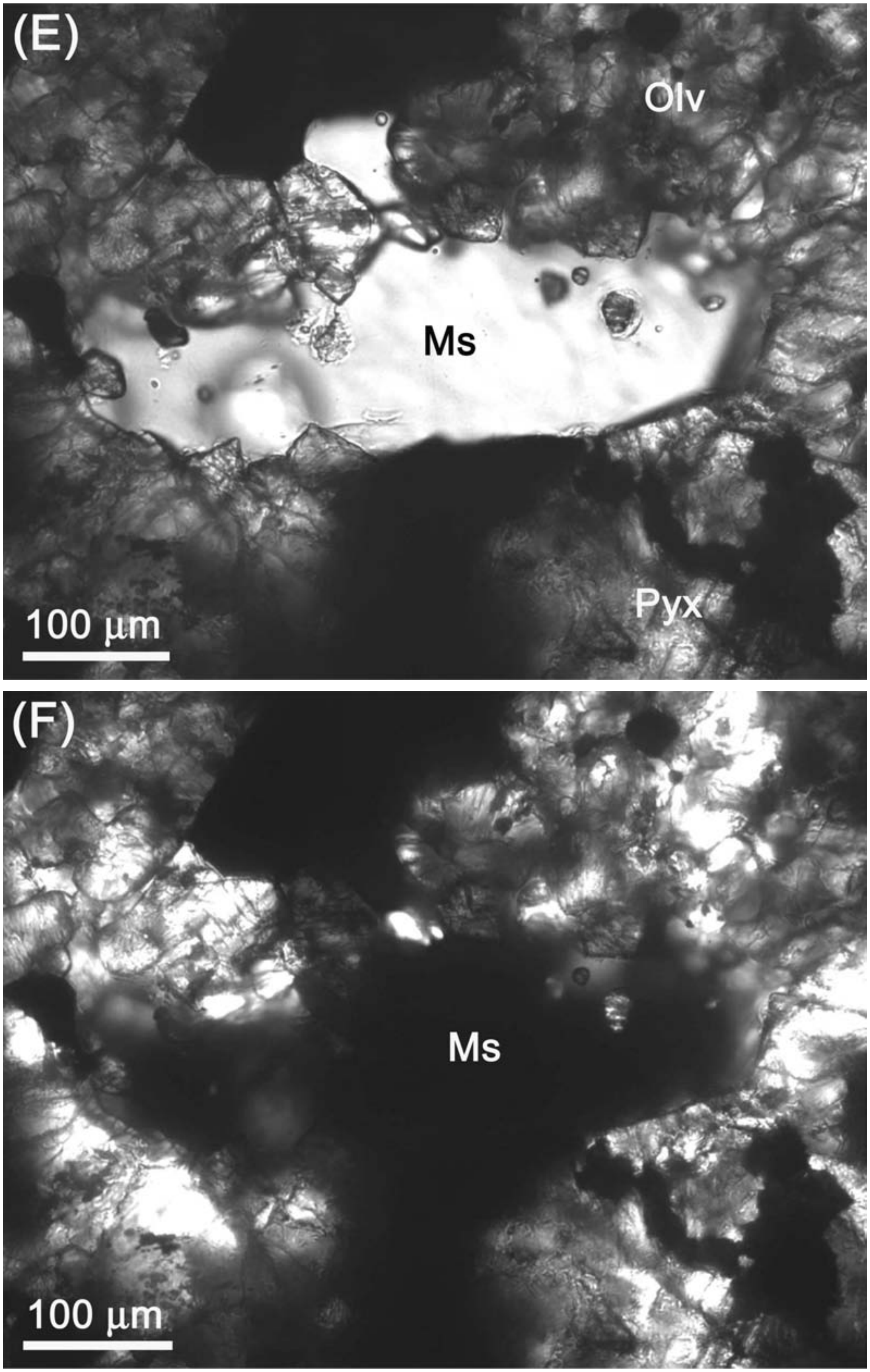

Fig. 2. *Continued.* Transmitted light images of a chondritic portion of the Suizhou meteorite: e) a plane polarized image indicating the occurrence of maskelynite. This image shows smooth and clear interior and no PDFs can be identified; f) a crossed polarized image of the same area in (e) showing completely isotropic maskelynite; Ms = maskelynite; Olv = olivine; Pyx = pyroxene.

composition intersecting the rock. No melt pocket of chondritic composition was observed. The shock veins ranging 20–200 μm in width extend for more than 10 to 20 cm in one direction. These thin veins do not form a complex network of veins (Fig. 1). The boundaries of the shock veins are sharp and straight.

High-Pressure Minerals in the Shock Veins

The shock veins of the Suizhou meteorite contain abundant high-pressure minerals including ringwoodite, majorite, majorite-pyrope garnet and $(Na, Ca)AlSi_3O_8$-hollandite (Xie et al. 2001), γ-$Ca_3(PO_4)_2$-tuite (Xie et al. 2003), and a high-pressure polymorph of chromite with a $CaTi_2O_4$-type structure (Chen et al. 2003). In this study, we confirmed the occurrence of each of these high-pressure minerals in the shock veins of the meteorite by using Raman spectroscopy, electron microscope, and EDS analyses. We observed that previous rock-forming and accessory minerals (including olivine, pyroxene, plagioclase, phosphates, and chromite) inside the shock veins were mostly transformed into their high-pressure polymorphs or were recrystallized as high-pressure phases.

Our analyses indicated that the shock veins contain two distinct lithologies: coarse-grained mineral aggregates and fine-grained matrix. The coarse-grained mineral aggregates have individual grains ranging up to 150 μm in size and consist mainly of ringwoodite, majorite, and hollandite that were transformed from the precursor olivine, low-Ca pyroxene, and plagioclase (Fig. 3). Coarse-grained high-pressure minerals usually occur as fragmental aggregates or are pseudomorphs of precursor minerals.

The fine-grained matrix of the shock vein is composed of a distinct liquidus phase assemblage of majorite-pyrope garnet, ringwoodite, and magnesiowüstite that crystallized from shock-induced chondritic melt (Fig. 4). The grain sizes of the liquidus phase garnet and ringwoodite are <3 μm and those of the magnesiowüstite are <1 μm. The Raman spectra of the majorite-pyrope garnet contain two typical strong bands at 662 and 928 cm^{-1} that are in agreement with the identification of Xie et al. (2001). The fine-grained ringwoodite can also be identified by two typical strong bands at 798 and 841 cm^{-1} observed by Raman spectroscopy. We did not obtain the Raman spectrum of magnesiowüstite. However, TEM and electron diffraction observations in the fine-grained matrix confirmed the magnesiowüstite (Xie and Wang, personal communication).

Ovoid Grains with Majorite Rim and $(Mg, Fe)SiO_3$ Glass Interior

Within the shock veins, we found some ovoid grains with crust-core structure in which the grains are up to 120 μm in size. These grains usually consist of a polycrystalline majorite

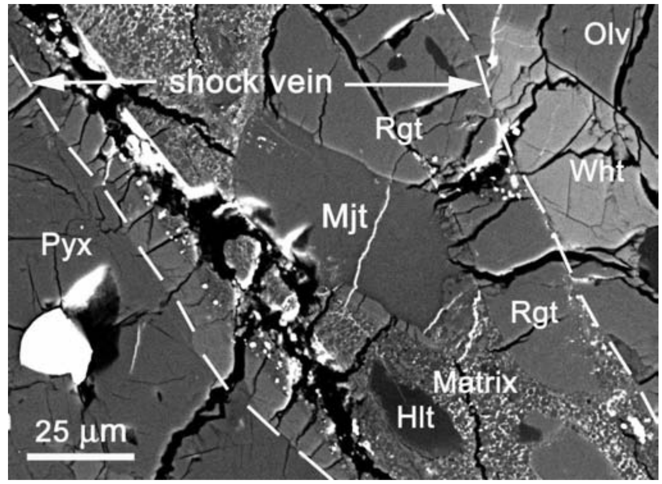

Fig. 3. A backscattered electron (BSE) image of the Suizhou meteorite showing that the shock vein contains coarse-grained, polycrystalline ringwoodite (Rgt), majorite (Mjt), and hollandite-structured polymorph of plagioclase (Hlt), as well as polycrystalline fine-grained matrix. Note that the majorite is a pseudomorph after pyroxene and shows a fine-grained polygranular texture; Olv = olivine; Pyx = pyroxene; Wht = whitlockite.

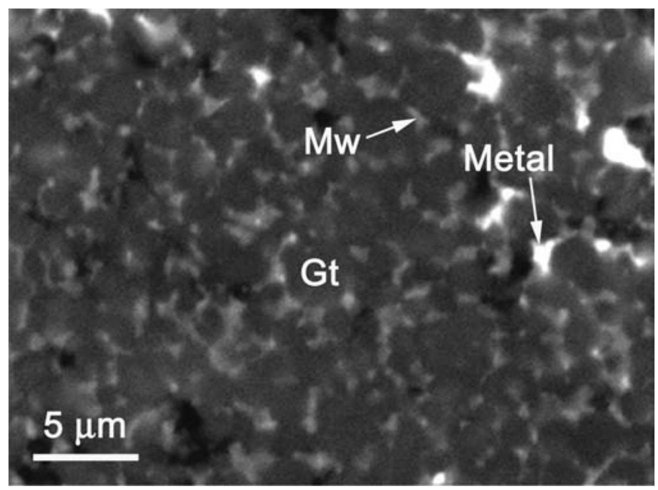

Fig. 4. The fine-grained matrix of the shock vein consists of majorite-pyrope garnet (Gt), magnisiowüstite (Mw), FeNi metal, and troilite.

rim surrounding an ovoid polygranular glassy silicate interior, and are surrounded by the fine-grained matrix of garnet, ringwoodite, magnesiowüstite, FeNi metal, and troilite (Figs. 5 and 6). The majorite rim and the glassy interior have a very similar fine-grained structure. The glassy interior is made of sub-round or ovoid pockets ranging 60–90 μm in length and 30–70 μm in width. The thickness of the majorite rim ranges between 5 and 30 μm. Abundant radiating fractures and cracks were observed in the majorite rim, whereby the cracks terminate at the surface of the glassy interior and the surrounding fine-grained matrix. High-magnification images revealed a granular texture of 1–3 μm in size in both the majorite rim and in the glassy phase. There is a rough and

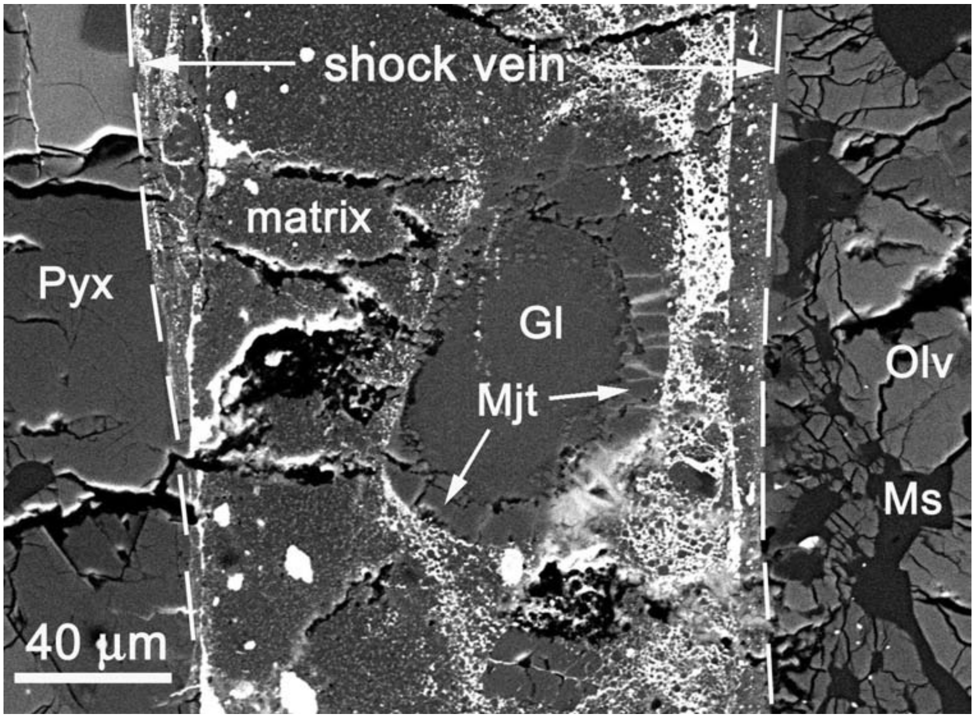

Fig. 5. A BSE image depicting an ovoid grain consisting of a majorite rim (Mjt) and a glassy interior (Gl) in the shock vein. The ovoid grain is surrounded by a fine-grained matrix composed of majorite-pyrope garnet, ringwoodite, magnesiowüstite, metal, and troilite. Note that the boundary between the majorite rim (Mjt) and the glassy interior (Gl) is rough and uneven, and that radiating fractures cross the majorite rim starting at the majorite-glass interface. The brighter material inside the shock veins represents metal-troilite; Olv = olivine; Pyx = pyroxene; Ms = maskelynite.

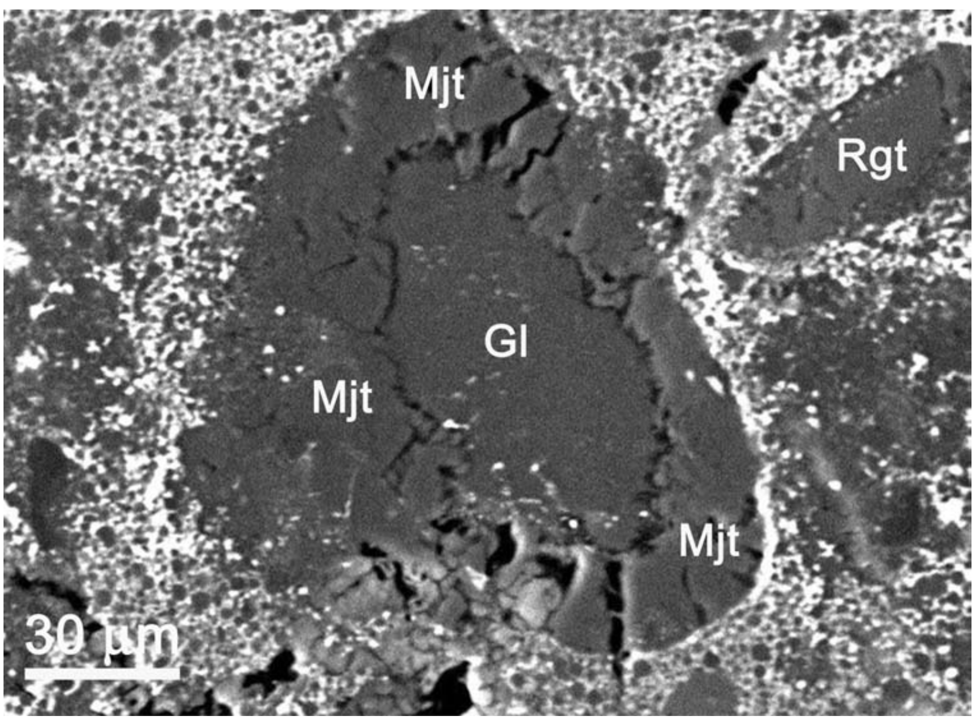

Fig. 6. An ovoid grain consisting of a majorite rim (Mjt) and a glassy interior (Gl) in the shock vein. The brighter spots in the glassy interior and the majorite rim are metal and troilite that could have been brought into the pyroxene along fractures before the phase transition took place. Note that the ovoid grain has a symmetric majorite rim; Rgt = ringwoodite.

Table 1. Electronic microprobe analyses of mineral phases in weight percent. SD represents standard deviation. The numbers in parentheses are analysis numbers.

	Low-Ca pyroxene		Majorite		Silicate glass		Majorite-pyrope garnet	
	(10)	SD	(7)	SD	(7)	SD	(8)	SD
SiO_2	55.82	1.07	55.71	0.99	55.86	1.04	50.42	1.11
TiO_2	0.20	0.05	0.15	0.04	0.17	0.05	0.12	0.02
Al_2O_3	0.16	0.07	0.26	0.06	0.35	0.05	3.71	0.47
FeO	13.64	0.33	13.48	0.41	12.95	0.38	13.73	0.40
MnO	0.43	0.05	0.46	0.03	0.50	0.07	0.47	0.03
MgO	28.28	0.57	28.50	0.49	28.37	0.41	28.05	0.47
CaO	0.73	0.04	0.80	0.07	0.74	0.05	1.92	0.11
Na_2O	0.03	0.01	0.10	0.01	0.08	0.03	0.91	0.04
K_2O	0.01	0.01	0.01	0.01	0.03	0.02	0.05	0.02
Cr_2O_3	0.13	0.04	0.15	0.05	0.18	0.03	0.41	0.06
Totals	99.43	–	99.62	–	99.23	–	99.79	–

uneven boundary between the majorite rim and the glassy interior. Small amounts of majorite inclusions of less than several micrometers in size occur in a narrow zone of ~5–10 μm in width in the glassy interior adjacent to the inner wall of the majorite rim. Some majorites extend as branches from the inner wall of the majorite rim into the glassy interior (Figs. 5 and 6). It appears that there is a zone consisting of a mixture of two materials, i.e., majorite plus glass.

Microprobe analyses show that the low-Ca pyroxene in the chondritic host, the majorite, and the glassy phase in the ovoid grains are identical in composition. In contrast, the liquidus phase majorite-pyrope garnet in the fine-grained matrix is relatively rich in Al_2O_3, CaO, Cr_2O_3, and Na_2O (Table 1).

The Raman spectrum of polycrystalline majorite, which is a kind of majorite grain containing no crust-core structure (Fig. 3), displays sharp strong bands at 926, 590 cm^{-1}, and weak bands at 315, 373, 654, 804, and 1056 cm^{-1} (Fig. 7). The Raman spectrum of majorite in the rim of the ovoid grain also displays sharp strong bands at 924 and 658 cm^{-1}, and weak bands at 316, 375, 538, 588, 802, and 1054 cm^{-1} (Fig. 7). The Raman spectra of these two kinds of majorite are in good agreement with the Raman spectra of majorite found in other chondritic meteorites (McMillan et al. 1989). The Raman spectrum of the ovoid grain's glassy interior contains only two broad bands at 976 and 666 cm^{-1} typical for MgO-SiO_2 glasses (Fig. 7), which could be attributed to Si-O stretching vibrations of SiO_4 tetrahedra and to the inter-tetrahedral Si-O-Si vibration, respectively (McMillan 1984a, b).

DISCUSSION

Formation of Ovoid Grains with Majorite Rim and (Mg, Fe)SiO_3 Glass Interior

The pressure and temperature history in the shock veins of meteorites can be well-constrained by high-pressure mineral assemblage (Chen et al. 1996). Based on the experimental data on a chondritic meteorite by Agee et al. (1995), the assemblage of garnet, ringwoodite, and magnesiowüstite in the shock veins of the Suizhou meteorite should have crystallized at pressures of 20–22 GPa and temperatures of 1800–2000 °C (Agee et al. 1995; Chen et al. 1996; Xie et al. 2001).

The majorite rim in the ovoid grains and their glassy interior have the same composition as low-Ca pyroxene of this meteorite. It is well-accepted that majorite in shocked meteorites was transformed from the precursor pyroxene (Smith and Mason 1970; Price et al. 1979; Chen et al. 1996). However, Price et al. (1979) suggested that shocked pyroxene first transforms into a prograde glass from which majorite subsequently crystallizes. Chen et al. (1996) indicated that the abundant dislocations and subgrain boundaries in majorite suggest that majorite forms by a solid-state mechanism. Therefore, we notice that the majorite rim in the ovoid grains of the Suizhou meteorite could not have crystallized from a shock-induced chondritic silicate melt because they lack an idiomorphic polycrystalline appearance and have the same composition as the matrix orthopyroxene. As we have shown in the BSE images (Figs. 5 and 6), majorite in the rim of ovoid grains have taken the pseudomorphic outlines of the precursor orthopyroxene fragments. In fact, polycrystalline majorites of up to 100 μm in diameter, which have transformed from a fragment of pyroxene, were found in the same veins of the Suizhou meteorite (Fig. 3) and many other meteorites (Smith and Mason 1970; Price et al. 1979; Langenhorst et al. 1995; Chen et al. 1996; Xie et al. 2001). The abundance of radiating fractures and cracks in the majorite rim shows that they were produced after the crystallization of majorite. Since these cracks terminate at the rim between the glassy interior and the surrounding fine-grained matrix, it appears that the cracks were caused by a volume increase that was induced by expansion through the amorphization of a pre-existing dense crystalline phase inside the glass.

One possibility is that the glass in the ovoid grain represents quenched silicate melt. One may argue then that some isolated liquid (Mg, Fe)SiO_3 droplets were enclosed in the high-pressure chondritic liquid. Such a liquid of unique pyroxene composition could never have survived without

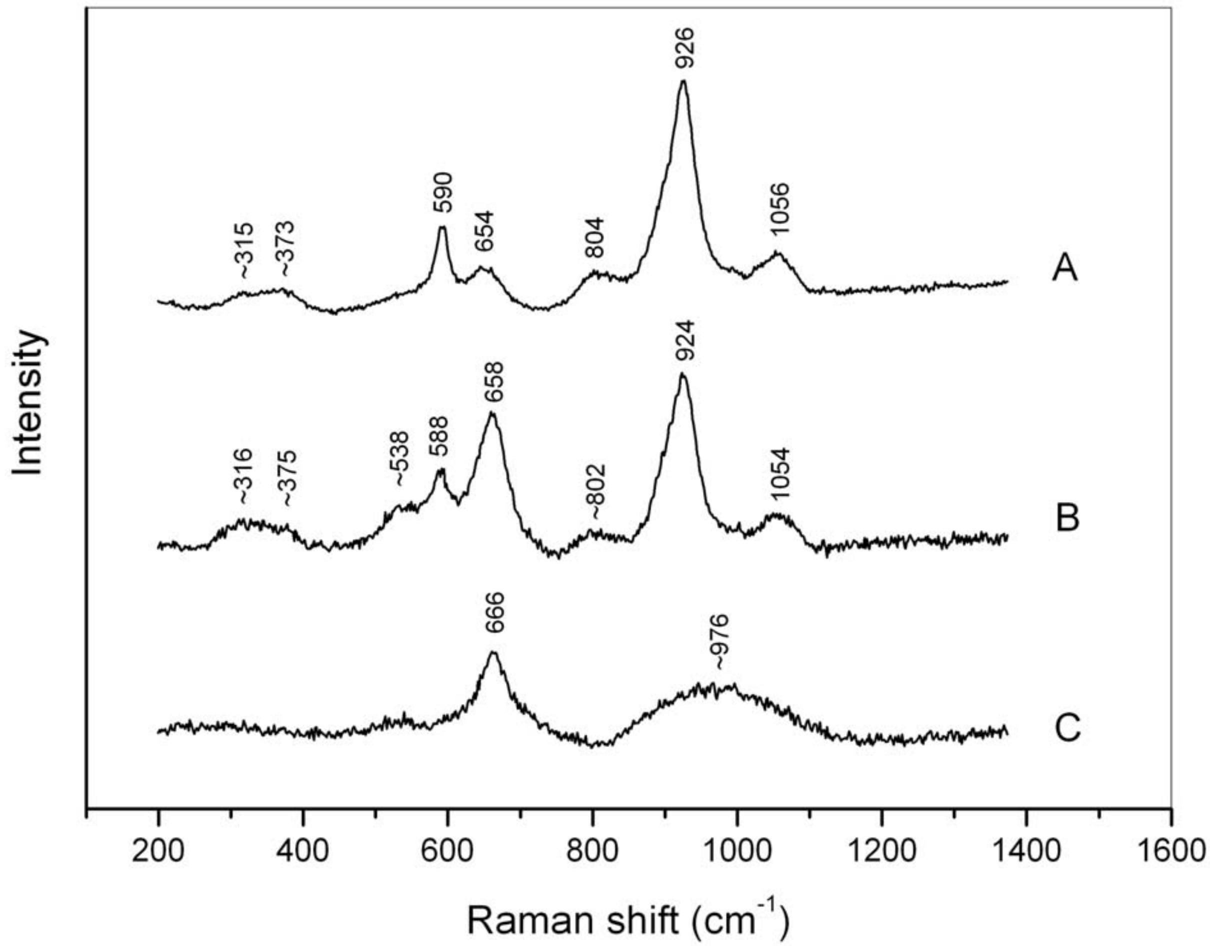

Fig. 7. The Raman spectra of majorite that contains no glassy core in Fig. 3 (a); majorite from the rim of an ovoid grain in Fig. 5 (b), and glass from the interior of an ovoid grain in Fig. 5 (c).

mixing with the surrounding chondritic liquid. In addition, the granular or equant texture of both the glassy interior and the majorite rim shows that the material in the interior of the ovoid grain, and likewise the majorite rim, was a polycrystalline phase before the amorphization of the former. The similarity in the texture of the majorite rim and the amorphous interior strongly suggests a common origin during a dynamic process. Furthermore, static high-pressure experiments never demonstrated that the orthopyroxene-majorite phase transition path goes via an intermediate glass phase (Agee et al. 1995; Herzberg and Zhang 1996; Wang and Takahashi 2000; Chen et al. 2004).

High-pressure experiments indicated that $MgSiO_3$ crystallizes in perovskite structures above 23 GPa and at ~2000 °C (Liu 1974, 1975; Gasparik 1993; Chen et al. 2004), and that $MgSiO_3$ majorite has a P-T stability field between 16 and 22.5 GPa and 1600–2500 °C (Gasparik 1993; Presnall 2000; Chen et al. 2004). So far, no crystalline (Mg, Fe)SiO_3 perovskite has ever been confirmed in natural assemblages. The best candidates for finding (Mg, Fe)SiO_3 perovskite are shock-metamorphosed meteorites. Sharp et al. (1997) reported a fine-grained assemblage of akimotoite plus amorphous (Mg, Fe)SiO_3 phase in the shock vein matrix of the Acfer 040 meteorite. These equant amorphous (Mg, Fe)SiO_3 grains, which are rich in Al_2O_3, CaO, and Na_2O, are believed to have formed as crystalline phase originally from shock-induced, dense melt. The formation of amorphous (Mg, Fe)SiO_3 was interpreted to have amorphized from perovskite after pressure release. It is known that the predominating high-pressure minerals in the Tenham meteorite are ringwoodite, majorite, garnet, and magnesiowüstite (Binns 1970; Price et al. 1979; Putnis and Price 1979; Mori and Takeda 1985; Langenhorst et al. 1995; Tomioka and Fujino 1997). However, Tomioka and Fujino (1997) reported the presence of (Mg, Fe)SiO_3 perovskite in the shock veins of the Tenham meteorite. The perovskite is found adjacent to some strongly deformed pyroxene fragments within the shock veins, showing that pyroxene was partially replaced by perovskite without melting. All previous results suggest that the peak-shock pressure and temperature in some meteorites may locally reach the stability field of perovskite. If the phase transition from pyroxene to perovskite has taken place, the peak pressure in the shock veins could be >23 GPa.

Although the shock veins experienced very high-pressure and temperature during the impact event, the temperature heterogeneities inside the veins can be recognized for most chondritic meteorites. It is well known that the shock veins of chondritic meteorites usually contain two kinds of lithologies, i.e., coarse-grained silicate fragments and fine-grained matrices (Chen et al. 1996). This suggests that not all chondritic constituents inside the shock veins reached a similar high-temperature during the shock event. Otherwise, the shock veins should have been composed of mainly one kind of lithology, for example, the fine-grained matrix, a solidified shock-induced chondritic melt. Evidently, some large fragments of silicates inside the shock veins experienced a heterogeneous temperature due to a process of thermal conductivity. It was reported that some pyroxene fragments inside the shock veins of a chondritic meteorite were partially transformed to a high-pressure, polymorph akimotoite only at the rim area of pyroxene grains (Tomioka and Fujino 1997), which indicates a higher temperature at the rim than in the interior of pyroxene fragments. In the case of the shock veins of the Suizhou meteorite, the large fragments' core of the precursor pyroxene grains that are enclosed in the shock-induced melt might have experienced a lower temperature than the rims that make contact with the melt. The P/T slope of the majorite-perovskite boundary is positive (Gasparik 1996), which indicates that majorite has higher temperature stability than perovskite. It appears that above 22 GPa the hotter rim of pyroxene would have transformed into majorite that is stable at a higher temperature than perovskite, however, the relatively cool cores of the pyroxene grains transformed into perovskite. After pressure release, the perovskite quickly vitrified due to a high post-shock temperature in the shocked meteorite, while the majorite was quenched. The vitrification of perovskite induces a volume increase due to relaxation, hence resulting in the formation of radiating expansion cracks in the majorite rim. In addition, it is extremely unlikely that the parental orthopyroxene was totally densified to majorite, the interior portion of which was preferentially vitrified while its outer rim remained intact.

The heating experiments and the molecular- and lattice-dynamics calculations indicated that the crystalline $MgSiO_3$ perovskite would be decompressed to an amorphous phase near the ambient pressure from its high-pressure stability fields at modest temperatures (Durben and Wolf 1992; Hemmati et al. 1995). The vitrification of $MgSiO_3$ perovskite begins above 127 °C and is complete by 477 °C at ambient pressure (Durben and Wolf 1992). The post-shock temperature must have been higher than 477 °C inducing a rapid vitrification of crystalline perovskite. To find crystalline (Mg, Fe)SiO_3 perovskite, one should look for very thin (<50 μm) shock-melt veins that have been quenched rapidly due to the loss of heat to the neighboring cold silicate matrix. We conclude that the (Mg, Fe)SiO_3 glassy phase in the Suizhou meteorite was most likely perovskite that was vitrified during the decompression stage at a post temperature higher than 477 °C.

Implications for Phase Transition in Shock Veins and Shock History

The finding of a large amount of (Mg, Fe)SiO_3 glassy phase, a vitrified perovskite, together with majorite has an important implication for phase transformation processes and the P-T history of shock veins. Majorite transformed from pyroxene has been widely observed in the shock veins of many chondritic meteorites (Smith and Mason 1970; Price et al. 1979; Putnis and Price 1979; Langenhorst et al. 1995; Chen et al. 1996; Sharp et al. 1997; Tomioka and Fujino 1997). This indicates that the impact-induced pressure and temperature conditions in the shock veins of many meteorites were suitable for the formation of majorite because of very high-pressure and temperature produced in these veins. Chen et al. (1996) reported that the pressure and temperature in the shock veins of the Sixiangkou meteorite could be up to 20–24 GPa and ~2000 °C, respectively. The pressures of 22–24 GPa are within the range for phase transformation of majorite-perovskite (Gasparik 1996). Abundant majorite and the lack of perovskite in the shock veins of the Sixiangkou meteorite (Chen et al. 1996) or only a small amount of perovskite in the Tenham meteorite (Tomioka and Fujino 1997) illustrate that the shock-induced temperature inside the veins could be high enough for the transition of pyroxene-majorite but the temperature could be too high for the phase transition from pyroxene to perovskite. The shock veins in the Suizhou meteorite (<0.2 mm in width) are much thinner than the shock veins in Sixiangkou, Tenham, and other meteorites (up to several mm in width). Thick shock veins, in which relatively large amounts of shock-induced melt were produced, must contain larger amounts of heat and could heat all material inside the veins to a homogeneous high-temperature. If the pyroxene fragments enclosed in thick shock veins were heated to a higher temperature, they would transform to majorite, not perovskite, though the pressure may be available for the transformation of pyroxene-perovskite. In contrast, thin shock veins may be available for the formation of perovskite because of temperature heterogeneity inside the veins. The relatively small amounts of heat within the thin vein could not heat all material in it to a homogeneous high-temperature in a short time. The transformation from pyroxene to perovskite may take place in the pyroxene heated to a relatively lower temperature. This study may offer a new approach to searching for the natural occurrence of perovskite in shocked meteorites.

According to the shock classification of meteorites, high-pressure minerals, including ringwoodite, would be produced only in the very strongly shocked meteorites (classified as shock stage 6) (Stöffler et al. 1991). Many previous studies did report that some chondritic meteorites with shock stage 6, such as Tenham L6 (Langenhorst et al. 1995), Sixiangkou L6 (Chen et al. 1996, 2002), and Acfer 040 L5-6 (Sharp et al. 1997), contain abundant high-pressure minerals in their shock veins. These meteorites were strongly shock-metamorphosed in the chondritic host in which plagioclase was mostly transformed into maskelynite (Stöffler et al. 1991; Chen and El Goresy 2000). However, such is not the case for the Suizhou meteorite. The shock-induced melting and shock veins are poorly developed in the Suizhou meteorite. Most plagioclases in the host meteorite remain intact in crystal structure. Only the plagioclase grains in a very limited area located close to the thin shock veins were transformed to maskelynite. According to the shock classification of chondritic meteorites (Stöffler et al. 1991), the Suizhou meteorite only matches shock stages 3–4, but its shock vein contains nearly all kinds of important high-pressure minerals including ringwoodite, majorite, "perovskite," majorite-pyrope garnet, (Na, Ca)$AlSi_3O_8$ hollandite, and magnesiowüstite. Our study shows that the shock veins containing abundant high-pressure minerals do not always occur in meteorites with higher shock levels (shock stage 6). A lower shock level of the whole rock and the developed thin veins with sharp boundaries at the wall material in the Suizhou meteorite characterize a mechanism in which the formation of veins was intimately related to shearing, compression, and friction melting within the meteorite (Stöffler et al. 1991). The strong deformation within the shock veins was not parallel to the shock-metamorphosed degree for the whole meteorite. Our study suggests that the occurrence of high-pressure minerals in the shock veins could not be used as a ubiquitous criterion for evaluating the shock stage of meteorites.

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