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The distinct morphological and petrological features of shock melt veins in the Suizhou L6 chondrite

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Abstract–The morphology and petrology of distinct melt veins in the Suizhou L6 chondrite have been investigated using scanning electron microscopy, electron microprobe analyses, and Raman spectroscopy, synchrotron energy-dispersive diffraction, and transmission electron microscopy. It is found that the melt veins in the Suizhou meteorite morphologically are the simplest, straightest, and thinnest among all shock veins known from meteorites. At first glance, these veins look like fine fractures, but petrologically they are solid melt veins of chondritic composition and consist of fully crystalline materials of two distinct lithological assemblages, with no glassy material remaining. The Suizhou melt veins contain the most abundant high-pressure mineral species when compared with all other veins known in chondrites. Thus, these veins in Suizhou are classified as shock veins. All rock-forming and almost all accessory minerals in the Suizhou shock veins have been transformed to their high-pressure polymorphs, and no fragments of the precursor minerals remain in the veins. Among the 11 high-pressure mineral phases identified in the Suizhou veins, three are new high-pressure minerals, namely, tuite after whitlockite, xieite, and the CF phase after chromite. On the basis of transformation of plagioclase into maskelynite, it is estimated that the Suizhou meteorite experienced shock pressures and shock temperatures up to 22 GPa and 1000 °C, respectively. Shearing and friction along shock veins raised the temperature up to 1900–2000 °C and the pressure up to 24 GPa within the veins. Hence, phase transition and crystallization of high-pressure minerals took place only in the Suizhou shock veins. Fast cooling of the extremely thin shock veins is regarded as the main reason that up to 11 shock-induced high-pressure mineral phases could be preserved in these veins.

INTRODUCTION

Heavily shocked chondritic meteorites, for example, those in the L and H groups, frequently contain shock-produced melt veins that have the same chemical composition as the chondritic host rock. Shock-induced melts occur in different textural settings and geometries in all groups of ordinary chondrites (e.g., Dodd and Jarosewich 1979; Dodd et al. 1982; Ashworth 1985). Stöffler et al. (1991) proposed to distinguish the following types of shock-induced localized melting (1) thin opaque melt veins, consisting of ‘‘mixed’’ melt products of rarely glassy, but mostly aphanitic, polycrystalline material formed by in situ melting of various mineral constituents; (2) melt pockets and interconnected irregular melt veins with aphanitic matrix and irregular boundaries to the host; (3) melt dikes, which consist of crystalline, mixed melt products, with fine-grained polycrystalline matrix and discordant boundaries to the host; and (4) sulfide and metal deposits injected into fractures in olivine and pyroxene that have frequently been referred as ‘‘shock blackening’’ in the literature.

Stöffler et al. (1991) reported that most of the melt veins in chondrites occur in irregular and curved forms and haphazardly traverse the chondritic meteorites. Sometimes, one vein branches into two or more veins, later feeding back into the main vein or continuing into different directions at oblique angles. For instance, the Pervomaisky (L6), Pinto Mountains (L6), and Cangas de Onis (H5) chondrites are intensely penetrated by branched black melt veins of variable width (tens of μm to 3 mm) (Stöffler et al. 1990; Semenenko and Golovko 1994). Pervasive networks of melt veins were observed in the Chantonnay, Pampa del Infierno, Sixiangkou, and some other L6 chondrites (Boctor et al. 1982; Dodd et al. 1982; Chen et al. 1996), as well as in the Yanzhuang H6 chondrite (Xie et al. 1991). For most vein-bearing chondrites, vein width ranges from 0.1 to 10 mm. The thickest shock vein observed by us measures 15 mm in the Yanzhuang H6 chondrite (Xie et al. 1991), but the average width for melt veins in chondrites is estimated at 0.5–1 mm. Only melt veins of L group chondrites were reported as occurrences of high-pressure phases such as ringwoodite, wadsleyite, majorite, among others (e.g., Binns et al. 1969; Smith and Mason 1970; Coleman 1977; Madon and Poirier 1979; Tomioka and Fujino 1997). Rubin (1985) pointed out that ringwoodite and majorite were found in melt veins of seven L6 chondrites. More recently, high-pressure minerals were also found in melt veins of many other L6 chondrites, such as Sixiangkou, Peace River, Mbale, Acfer-040, Suizhou, Yamato (Y)-791384, Y-74445, Umbarger, and S-98222 (Chen et al. 1996, 1998; Sharp et al. 1997; Kimura et al. 2000; Xie et al. 2001, 2002; Ozawa et al. 2009). However, tiny ringwoodite grains were identified by Raman spectroscopy in the heavily shock-metamorphosed mosaic olivine of the Yanzhuang H6 chondrite (Chen and Xie 1993). Ringwoodite, majorite, and lingunite ($NaAlSi_3O_8$-hollandite) were also observed in the Antarctic H-group Y-95267 (H6) and Y-75100 (H6) chondrites (Kimura et al. 2000, 2003).

The Suizhou meteorite fell on April 15, 1986 at Dayanpo, Suizhou City, Hubei Province, China. This meteorite consists of the rock-forming minerals olivine, low-Ca pyroxene, plagioclase, FeNi-metal, and troilite, and the accessory components whitlockite, chlorapatite, chromite, and ilmenite. The Suizhou meteorite was classified as an L6 chondrite (Wang and Li 1990), and was evaluated as a moderately to strongly shock-metamorphosed (S4 to S5) meteorite due to the presence of mosaicism in olivine and transformation of plagioclase to maskelynite (Xie et al. 2001; Chen et al. 2008). The determination of the cosmogenic nuclides of ^{3}He, ^{21}Ne, ^{35}Ar, ^{83}Kr, and ^{126}Xe, as well as the results of ^{81}Kr-Kr dating, indicate that the Suizhou meteorite has an average cosmic-ray exposure age of 30.8 ± 3.3 Ma. This implies that the parent body of the Suizhou meteorite experienced a collision event at about 31 Ma ago (Wang and Li 1990).

In comparison to other L6 chondrites containing shock veins up to several millimeters in width (Price et al. 1979; Rubin 1985; Chen et al. 1996), the Suizhou meteorite contains only a few very thin black melt veins ranging from 0.02 to 0.09 mm in width. Morphologically, the thin Suizhou melt veins look like fine parallel fractures traversing the chondritic meteorite but they are distinct straight solid melt veins. Petrologically, they are chondritic in composition and consist of two distinct high-pressure mineral assemblages (1) coarse-grained polycrystalline ringwoodite, majorite, and lingunite that are formed through the solid state transformations of olivine, low-calcium pyroxene, and plagioclase, respectively and (2) fine-grained majorite-pyrope garnet in solid solution + magnesiowüstite that crystallized at high pressures and temperatures from shock-induced dense chondritic melt (Xie et al. 2001). Fine-grained garnet + magnesiowüstite, together with FeNi-metal and troilite intergrowths, make up the matrix of the vein. It is interesting that our transmission electron microscopic study revealed that the Suizhou vein matrix consists of fully crystalline material with no glassy material remaining. In this article, we describe the distinct morphological and petrological features of the shock melt veins in the Suizhou L6 chondrite, and discuss the formation mechanism of these veins.

SAMPLES AND METHODS

Polished thin sections were prepared from fragments of the Suizhou meteorite that contain black vein material. The petrology and composition of the samples were investigated by a MPV-SP optical microscope in both transmitted and reflected light, a Hitachi S-3500N scanning electron microscope (SEM) in backscattered electron mode and equipped with a Link ISIS 300 X-ray energy-dispersive spectrometer at the Guangzhou Institute of Geochemistry, Chinese Academy of Sciences (CAS), and a Cameca SX-51 electron microprobe using 15 kV accelerating voltage and 10 nA specimen current at the Institute of Geology and Geophysics, CAS. Raman spectra of minerals were recorded with a Renishaw R-2000 Raman instrument at the Guangzhou Institute of Geochemistry, CAS, to characterize mineral structures. A microscope was used to focus the excitation beam (Ar^{+} laser, 514 nm line) to a 2 to 3 μm spot and to collect the Raman signal. Raman spectra were accumulated for 150 s. A Hitachi H-800 transmission electron microscope (TEM) in bright field mode at 120 kV with selected area electron diffraction (SAED) analysis at Wuhan University of Technology was used to study the mineral composition of the vein matrix. Ion-beam milling in a Gatan 691 precision ion polishing system was used to prepare the electron transparent samples. The synchrotron energy-dispersive diffraction technique at the beam-line X17C of the National Synchrotron Light Source (NSLS), Brookhaven National Laboratory (2.584 GeV, 100 mA) was also used to identify the mineral constituents of the

Suizhou vein matrix. The X-ray beam was collimated to a size of 15×15 μm, and was focused on the probed mineral sample in the polished thin section. Energy dispersive X-ray diffraction was gathered with an intrinsic germanium detector.

RESULTS

Morphological Features of the Suizhou Melt Veins

1. Compared with the irregular-shaped, curved, or branched melt veins, and some of the complex or network-like melt veins in many L and H group chondrites, the melt veins in the Suizhou meteorite are the simplest.

For instance, Coleman (1977) described a network of dark veins on a sawn surface of the Catherwood L6 chondrite. Dodd et al. (1982) reported the first occurrence of complex veins in the Chantonnay L6 chondrite, in which an early formed vein containing abundant chondritic xenoliths is intersected by a late vein composed of a fine-grained matrix. Boctor et al. (1982) found complex vein geometries in the form of networks in the Pampa del Infierno chondrite. The well-known Peace River L6 meteorite also consists of a severely deformed chondrite mass and a network of melt veins up to 3 mm in width (Chen et al. 1998). A network of dark veins was also observed in the Sixiangkou L6 chondrite, which contains a number of curved and branched veins intersecting the chondritic host (Fig. 1). More recently, we identified shock-produced complex veins, including earlier and later veins, in this Sixiangkou chondrite. The early veins are intersected by the later veins and consist of both coarse-grained aggregates of ringwoodite, majorite, and lingunite, and fragments of olivine, pyroxene, plagioclase, metal, and troilite, as well as a fine-grained matrix of garnet, ringwoodite, metal, and troilite. The later veins mainly consist of a fine-grained matrix of garnet, magnesiowüstite, metal, and troilite, with a small amount of coarse-grained aggregates composed of ringwoodite and majorite (Chen and Xie 2008). The Yanzhuang H6 chondrite was also found to consist of a chondritic matrix and a network of melt veins ranging in width from 0.1 to 15 mm, and melt pockets up to 30 mm in size (Xie et al. 1991; Chen et al. 1998). A network of dark shock veins penetrating the entire chondritic rock is also observed in the Yanzhuang chondrite studied here (Fig. 2).

The morphology of Suizhou melt veins is remarkably different from that in most chondritic meteorites. Figure 3 shows four thin melt veins in a large Suizhou fragment of 1.434 kg mass. All of them are single veins. Among them, three are parallel to each other and extend in the same direction, and the fourth is an oblique vein joining the middle one of the three others at an angle of about 45°. Neither intersection of veins nor a vein network was observed in the fragment. Hence, we assume that the melt veins in the Suizhou L6 chondrite are the simplest single veins in comparison with those in other vein-bearing chondrites.

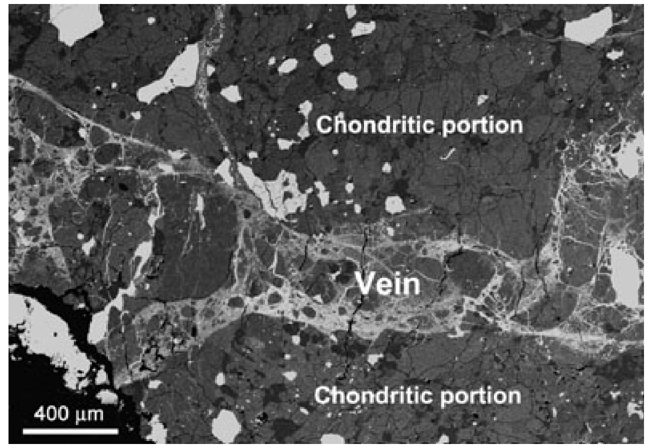

Fig. 1. Backscattered electron (BSE) image of a polished thin section of the Sixiangkou L6 chondrite showing the occurrence of a melt vein (Vein). Note the curved and jagged boundaries between the vein and the chondritic portion and a branched veinlet.

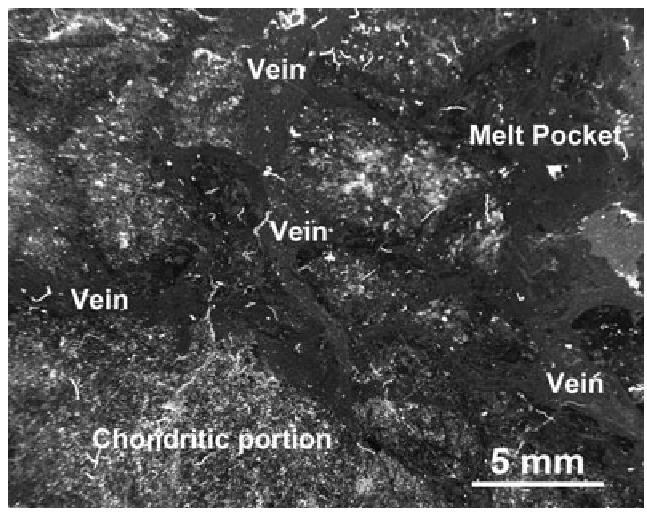

Fig. 2. Photograph of sawn surface of the Yanzhuang H6 chondrite showing a network of dark melt veins (Vein). Note a melt pocket in the upper right part of the photograph.

2. The melt veins in the Suizhou meteorite are also the straightest compared with the curved or irregular melt veins in many other chondrites.

It is known that melt veins in most chondritic meteorites occur in curved form and show irregular vein boundaries to the host chondrite. For instance, the

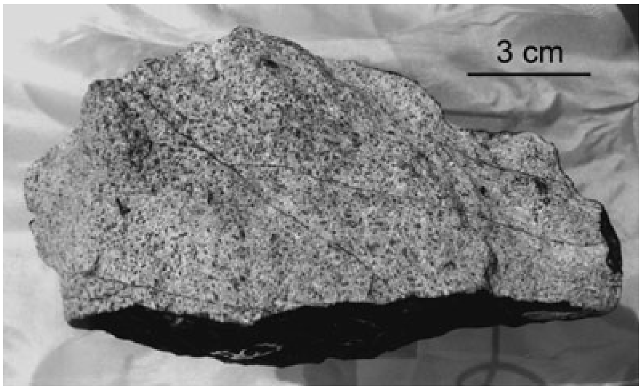

Fig. 3. Photograph of a fragment of the Suizhou meteorite showing three thin parallel and one oblique melt vein (black lines).

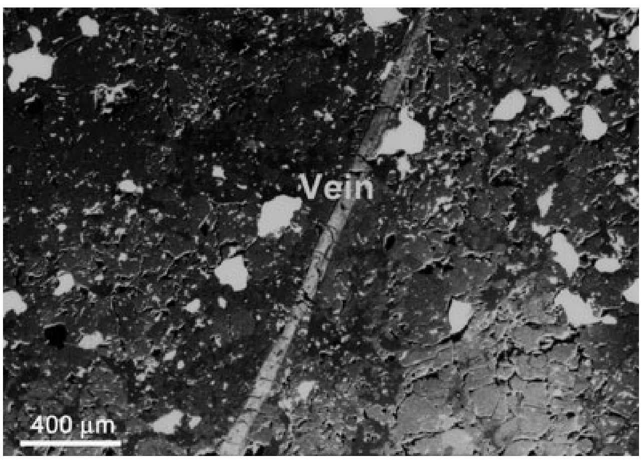

Fig. 4. Backscattered electron image showing a solid, straight, and thin melt vein (Vein) with sharp vein boundaries to the host chondrite.

Tenham, Coorara, Catherwood, and Coolaman chondrites contain irregular or complex melt veins traversing the chondritic meteorites (Steele and Smith 1978). The networks of dark veins observed in the Peace River, Pampa del Infierno, and Sixiangkou L6 chondrites, as well as in the Yanzhuang H6 chondrite, also display irregular vein edges. On the other hand, melt veins in the Suizhou meteorite are quite regular and show very straight vein boundaries. Figures 4 and 5 show some very straight melt veins in the Suizhou meteorite that have knife-sharp boundaries to the host chondrite on both sides of the veins. Furthermore, we observed that molten troilite often occurs in the form of straight thin stringers of more than 100 μm length and less than 3 μm width along the boundaries of a vein bordering the unmelted part of the meteorite (Fig. 5a). It should be pointed out that neither melt dikes nor melt pockets were observed in the Suizhou meteorite. Therefore, it is reasonable to assume that the shock-produced melt veins in the Suizhou chondrite are the straightest in comparison with those in most vein-bearing chondrites.

3. The melt veins in the Suizhou meteorite are the thinnest among all other shock-vein-bearing meteorites.

It has been reported that shock melt veins in chondritic meteorites are about 1 mm in width, such as those in the Tenham, Coorara, Catherwood, and Coolaman L6 chondrites (Steele and Smith 1978). Some variations in vein thickness were observed in different meteorites, but it is hard to find veins thinner than 0.1 mm in most of these cases. For instance, the shock veins in Catherwood meteorite range from 0.1 to 10 mm in apparent width, and the average true width is estimated to be 0.5 mm (Coleman 1977). The width of Sixiangkou shock veins ranges from tens of micrometers to 10 mm. Besides some simple veins with thicknesses less than 200 μm, there are complex veins with thickness ranging from 200 μm to 10 mm (Chen and Xie 2008). However, almost all the melt veins in the Suizhou chondrite are thinner than 0.1 mm in width, namely, 0.05–0.09 mm, and we have observed only one case where the vein width locally reached 0.2 mm. Figures 3 and 4 demonstrate that the shock veins traversing the whole body of a Suizhou fragment are very thin (on average, <0.1 mm in width) and the vein width remains rather uniform.

Petrological Features of the Suizhou Melt Veins

1. Evidence shows that black fracture-like features in the Suizhou meteorite are solid melt veins.

It is interesting to point out that at first glance the Suizhou black veins look like fine fractures traversing the chondritic body of the meteorite; however, they are single and straight solid melt veins (Fig. 4). They are chondritic in mineralogical composition and consist of fine-grained vein matrix and comparatively coarse-grained mineral fragments that are randomly distributed in the matrix (Fig. 5).

Our microscopic study revealed that the fine-grained matrix of the Suizhou shock veins makes up about 80–90 vol% of the veins, and the remaining 10–20 vol% of the veins consist of coarse-grained mineral fragments (Xie et al. 2001). With the SEM and Raman spectroscopy, the vein matrix is revealed to be composed of numerous tiny euhedral crystals of garnet with 1–5 μm size, which indicates that they crystallized at high pressure and high temperature from dense chondritic melt (Fig. 6). Tiny irregular grains of magnesiowüstite and ringwoodite are located in the interstices between garnet crystals. Eutectic intergrowths of FeNi-metal and troilite that crystallized during

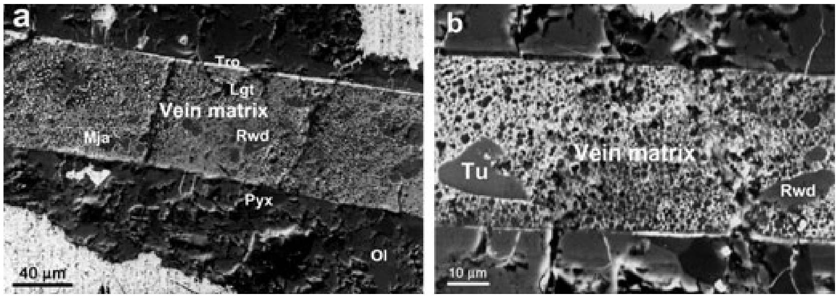

Fig. 5. Backscattered electron images showing straight melt veins with sharp vein boundaries to the host chondrite. a) BSE image showing the two distinct lithological assemblages: fine-grained vein matrix and coarse-grained mineral fragments of ringwoodite (Rwd), majorite (Mja), and lingunite (Lgt). Note the straight thin stringers of molten troilite (Tro) along the upper boundary of the vein. Ol, olivine; Pyx, pyroxene. b) BSE image showing coarse-grained fragments of ringwoodite and tuite (Tu) in the vein matrix.

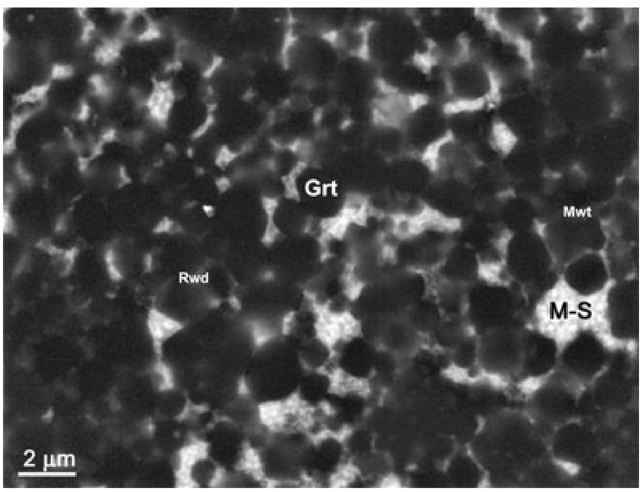

Fig. 6. Backscattered electron image showing the mineral constituents of the Suizhou vein matrix. Grt, majorite-pyrope garnet in solid solution; Mwt, magnesiowüstite; Rwd, ringwoodite; M-S, metal-troilite intergrowth.

meteorite cooling also occur in the matrix of the veins (Fig. 6). On the other hand, the coarse-grained clast assemblage comprises different high-pressure mineral phases that were formed through solid state transformation of silicate, phosphate, and oxide minerals (Xie et al. 2001, 2003, 2005; Chen et al. 2003). This demonstrates that these melt veins represent shock veins.

2. The Suizhou vein matrix consists of fully crystalline material—no glassy material remains.

Stöffler et al. (1990) reported that the shock veins in many chondritic meteorites rarely consist of glassy, and mostly of aphanitic, polycrystalline material formed from in situ melted mineral constituents. Our microscopic, SEM, and TEM studies on the mineral composition of veins in Yanzhuang H6 and Sixiangkou L6 chondrites have indicated that glassy material can always be observed in veins with widths of several millimeters (Chen et al. 1998; Chen and Xie 2008). However, our SEM and TEM studies on Suizhou vein matrix revealed that besides the metal-troilite eutectic intergrowths that solidified at the last stage of vein formation, the matrix is composed of three fine-grained high-pressure mineral phases with good crystallinity; no glassy material was detected. The fine-grained crystalline high-pressure minerals are as follows.

a. Equant idiomorphic majorite-pyrope garnet crystals are the first product of crystallization from the shock-produced dense silicate melt (Figs. 7a–c). Microprobe analyses showed that this garnet mineral contains a much higher content of Al_2O_3 (3.51 wt%) than that in Suizhou pyroxene (0.16 wt%) and relatively coarse-grained majorite (0.16 wt%). The synchrotron radiation X-ray diffraction (SRXRD) patterns of this phase show 16 diffraction reflections (Table 1). The strongest lines are at 2.572 Å (intensity 100), 2.880 (70), 1.539 (70), 2.453 (50), and 1.597 (40). These data are identical to those for standard majorite in JCPDS No. 25-0843, and our data can be considered as the characteristic X-ray diffraction patterns for the liquidus majorite-pyrope garnet. It is also worth mentioning that the diffraction peaks obtained for majorite-pyrope garnet are sharp enough to indicate good crystallinity of this mineral.
b. Irregular polycrystalline grains of magnesiowüstite, (Mg,Fe)O, fill the interstices between garnet crystals (Figs. 7a–e). Their SAED patterns show sharp diffraction spots of magnesiowüstite (insets of Figs. 7a and 7d), and the calculated strong diffraction lines are 2.120 (100), 1.492 (60), and 2.439 (40) Å (Table 2), which can be compared with those of periclase (MgO) in JCPDS No. 4-289.

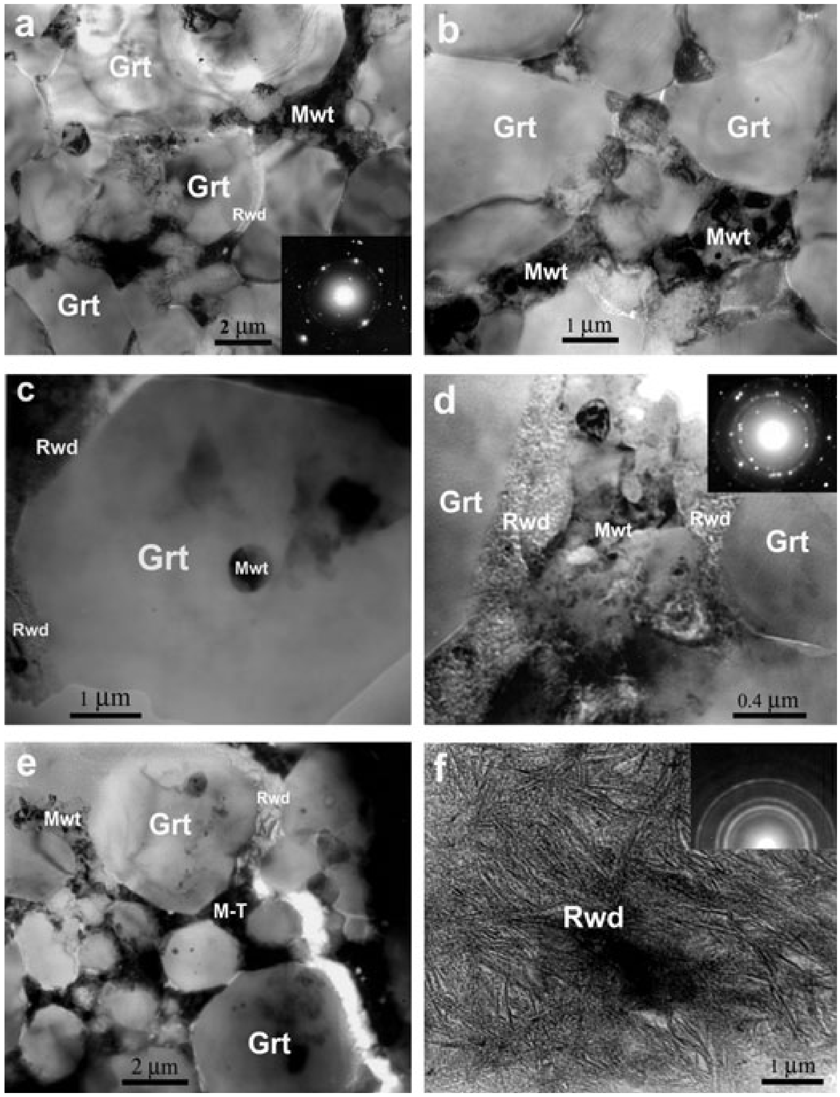

Fig. 7. Transmission electron microscopy bright field images showing the fine-grained high-pressure minerals in Suizhou shock vein matrix. a, b) TEM images showing the aggregate of idiomorphic crystals of majorite-pyrope garnet (Grt) and irregular microcrystalline magnesiowüstite (Mwt) and ringwoodite (Rwd) in interstices between garnet crystals. Inset in (a) is the SAED pattern of magnesiowüstite. c) A TEM image showing a euhedral garnet (Grt) crystal surrounded by microcrystalline ringwoodite (Rwd). Note the small inclusions of magnesiowüstite (Mwt) in garnet. d) A TEM image showing the fine-granular ringwoodite (Rwd) between garnet (Grt) and magneisowüstite (Mwt) grains. Inset is the SAED pattern showing both diffraction spots of magneisowüstite and diffraction rings of fine-granular ringwoodite. e) A TEM image showing the fine-blocky ringwoodite (Rwd) between garnet (Grt) and magnesiowüstite (Mwt) grains. Note a small FeNi metal + troilite (M + T) grain in the center of the image. f) A TEM image showing the fiber-like ringwoodite (Rwd). Inset is the SAED pattern showing diffraction rings of fiber-like ringwoodite.

The slight increase of *d*-values is due to the presence of FeO in its composition.

c. Polycrystalline ringwoodite occurs in the form of fine-granular (Figs. 7c and 7d), blocky (Fig. 7e), or fiber-like (Fig. 7f) narrow bands between garnet crystals or between garnet and magnesiowüstite grains. Their SAED patterns show only rather sharp concentric diffraction rings. The calculated strongest four diffraction lines are at 2.446 (100), 2.028 (70), 1.434 (60), and 2.872 (30) Å (Table 3), which is identical to the reflections of ringwoodite in JCPDS No. 21-1258.

3. Abundant coarse-grained high-pressure minerals occur in Suizhou veins.

Besides the three fine-grained high-pressure minerals occurring in matrix, the Suizhou shock veins also contain more abundant coarse-grained high-pressure mineral species, in comparison with all other

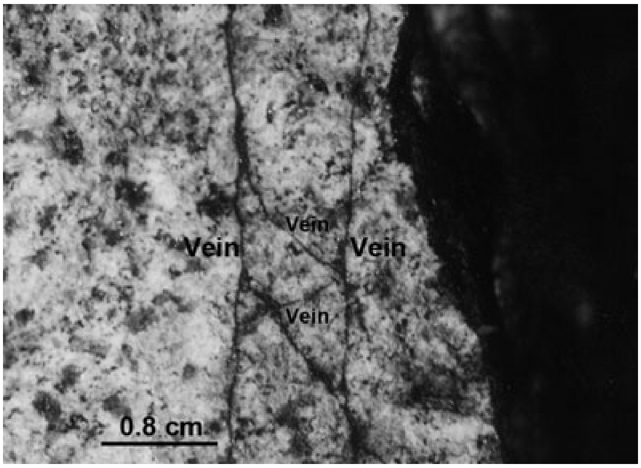

Fig. 8. Photograph of part of a Suizhou meteorite fragment showing the diagonal melt veins (Vein) in between two main parallel shock veins.

Table 1. Synchrotron radiation X-ray diffraction data of majorite-pyrope (Maj-Prp) garnets in the Suizhou vein matrix.

Maj-Prp garnet #1 in vein matrix		Maj-Prp garnet #2 in vein matrix		Majorite garnet JCPDS No. 25-0843	
d (Å)	*I*	*d* (Å)	*I*	*d* (Å)	*I*
2.880	70	2.880	70	2.881	70
2.572	100	2.571	100	2.575	100
2.453	50	2.451	40	2.454	45
2.350	35	2.349	35	2.352	30
2.256	35	2.255	30	2.262	35
2.104	10	2.105	10	2.103	18
2.038	20	2.037	30	2.038	25
1.865	50	1.863	25	1.868	25
1.821	10	1.820	10	1.820	10
1.662	20	1.661	20	1.663	20
1.597	40	1.596	30	1.597	40
1.539	70	1.538	50	1.540	60
1.438	10	1.438	10	1.439	17
1.288	10	1.288	15	1.288	15
1.257	15	1.256	10	1.258	20
1.228	15	1.228	10	1.228	14

vein-bearing chondrites. Almost all rock-forming and accessory minerals in the Suizhou shock veins have been transformed to their high-pressure polymorphs, and no fragments of the precursor minerals remain in the veinlets.

Rubin (1985) pointed out that only two high-pressure minerals, ringwoodite and majorite, were found in the shock veins of seven L6 chondrites. In recent years, more and more high-pressure phases have been identified in some shocked chondrites (Chen et al. 1995, 1996, 2003, 2008; Sharp et al. 1997; Tomioka and Fujino 1997; Gillet et al. 2000; Xie et al. 2001, 2003; Kimura et al. 2000, 2001; Xie et al. 2002; Xie and Sharp 2007; Ozawa et al. 2009). Table 4 summarizes the high-pressure phases identified in shock veins of different L and H group chondrites. Among 19 shock vein-bearing chondrites, 12 contain only 1–3 high-pressure phases, 5 meteorites contain 4–6 high-pressure phases, 1 meteorite contains 7 high-pressure phases, and only the Suizhou meteorite contains 11 high-pressure phases. Hence, we assume that the Suizhou chondrite is the meteorite with the most abundant high pressure-mineral occurrence, although the shock veins in Suizhou are extremely thin.

Our SEM, TEM, and Raman spectroscopic studies revealed that besides the above-mentioned fine-grained assemblage crystallized from shock melt, and the FeNi metal and troilite (FeS), which were molten and occur

Table 2. Selected area electron diffraction data of fine-grained magnesiowüstite in the Suizhou vein matrix.

Fine-grained Mg-wüstite #1 in vein matrix		Fine-grained Mg-wüstite #2 in vein matrix		Periclase (MgO) JCPDS No. 4-289	
d (Å)	*I*	*d* (Å)	*I*	*d* (Å)	*I*
2.439	40	2.437	70	2.431	20
2.120	100	2.116	100	2.106	100
1.492	50	1.499	60	1.489	60
1.273	20	1.275	30	1.270	25
1.216	15	1.218	15	1.216	15
1.065	20	1.065	20	1.055	15
0.968	15	0.963	20	0.966	10
0.946	10	0.945	20	0.942	15
0.887	10	0.886	15	0.860	15
0.8201	10	0.821	10	0.811	3

Table 3. Selected area electron diffraction data of fine-grained ringwoodite in the Suizhou vein matrix.

Fine-grained ringwoodite #1 in vein matrix		Fine-grained ringwoodite #2 in vein matrix		Ringwoodite JCPDS No. 21-1258	
d (Å)	*I*	*d* (Å)	*I*	*d* (Å)	*I*
2.872	30	2.879	20	2.872	20
2.446	100	2.445	100	2.447	100
2.028	70	2.027	70	2.028	40
–	–	1.661	5	1.656	< 5
1.555	20	1.561	20	1.560	20
1.434	60	1.436	60	1.434	60
1.240	20	1.237	10	1.237	< 5
1.170	15	1.176	10	1.172	10
1.021	15	1.015	15	1.014	5
0.901	10	0.901	10	0.907	< 5
–	–	0.852	10	0.850	< 5
0.826	10	0.828	10	0.828	10

Table 4. Shock-produced high-pressure minerals in the shock melt veins of ordinary chondrites.

Meteorite	Group	High-pressure minerals in veins[a]	Reference
Suizhou	L6	Rwd, Mja, Lgt, Akm, Prv, Mwt, Grt, Tu, Xie, CF, A-phase	Xie et al. (2001, 2003), Chen et al. (2003)[b]
Sixiangkou	L6	Rwd, Wds, Mja, Lgt, Mwt, Grt, A-phase	Chen et al. (1995, 1996), Gillet et al. (2000)
Tenham	L6	Rwd, Mja, Ca-Mja, Lgt, Akm, Prv	Binns et al. (1969), Xie et al. (2006), Xie and Sharp (2007)
Y-74445	L6	Rwd, Wds, Mja, Lgt, Akm, Jd	Kimura et al. (1999), Ozawa et al. (2009)
Umbarger	L6	Rwd, Akt, Lgt, Fe-Spl, Sti	Xie et al. (2002)
Y-95267	H6	Rwd, Wds, Mja, Akm, Lgt	Kimura et al. (2003)
Y-75100	H6	Wds, Mja, Jd, Lgt	Kimura et al. (2000)
Peace River	L6	Rwd, Wds, Grt	Sharp et al. (1996), Chen et al. (1998)
Mbale	L6	Rwd, Wds, Grt	Sharp et al. (1996), Chen et al. (1998)
Acfer 040	L5-6	Rwd, Akm, Prv	Sharp et al. (1997)
Y-791384	L6	Rwd, Mja, Lgt	Kimura et al. (2000)
Yanzhuang	H6	Rwd, Mja	Chen and Xie (1993)
Catherwood	L6	Rwd, Mja	Coleman (1977)
Coorara	L6	Rwd, Mja	Smith and Mason (1970)
Coolaman	L6	Rwd, Mja	Smith and Mason (1970)
Roy	L5	Rwd, Mja	Xie et al. (2006)
S-98222	L6	Wds, Jd	Ozawa et al. (2009)
Y-791099	LL5/6	Jd	Kimura et al. (2001)
Y-791108	LL5/6	Jd	Kimura et al. (2001)

[a]Rwd = ringwoodite; Mja = majorite; Lgt = lingunite; Akm = akimotoite; Prv = perovskite; Mwt = magnesiowüstite; Grt = garnet; Tu = tuite; Xie = xieite; CF = $CaFe_2O_4$-polymorph of chromite; A-phase = high-pressure phase of chlorapatite; Wds = wadsleyite; Ca-Mja = Ca-rich majorite; Fe-Spl = Fe_2SiO_4-spinel; Sti = stishovite; Jd = jadoite.
[b]Also Chen et al. 2003, 2004, 2008.

as fine eutectic FeNi-FeS intergrowths in the interstices between fine-grained high-pressure minerals, all coarse-grained rock-forming silicate minerals in the Suizhou shock veins, such as olivine, pyroxene, and plagioclase, and almost all accessory phosphate and oxide minerals, such as whitlockite, chlor-apatite, and chromite, have been transformed to their high-pressure polymorphs. The only missing accessory mineral in veins is the oxide mineral ilmenite, which might have been dissolved in the shock melt. These findings are unique for all studied chondrites because the shock melt veins in many chondrites contain not only high-pressure mineral phases but also fragments of intact olivine, pyroxene, plagioclase, and chromite.

4. Three new high-pressure minerals were first identified in the Suizhou shock veins.

Among the 11 high-pressure mineral phases found in Suizhou shock veins, eight were first identified in other L6 chondrites. These are ringwoodite (the spinel-structured polymorph of olivine), majorite (the garnet-structured polymorph of pyroxene), akimotoite (the ilmenite-structured polymorph of pyroxene), vitrified perovskite (the perovskite-structured polymorph of pyroxene), lingunite (the hollandite-structured polymorph of plagioclase), majorite garnet in solid solution with pyrope, and magnesiowüstite.

The other three new high-pressure phases we found in the Suizhou veins are tuite, the high-pressure polymorph of whitlockite (Xie et al. 2002, 2003), xieite, the $CaTi_2O_4$-structured polymorph of chromite (Chen et al. 2003, 2008), and the CF phase, the $CaFe_2O_4$-structured polymorph of chromite (Chen et al. 2003). Tuite is considered the first fully identified high-pressure phosphate mineral ever found in natural materials. Xieite and the CF phase are two postspinel high-pressure phases that were predicted 40 yr ago by Reid and Ringwood (1969, 1970), who proposed orthorhombic $CaFe_2O_4$-type and $CaTi_2O_4$-type structures as the top candidates for ''postspinel'' transitions in the Earth's mantle. Hence, the finding of these phases in the Suizhou meteorite is significant for the study of Earth's mantle mineralogy.

ORIGIN OF SHOCK VEINS IN THE SUIZHOU METEORITE

It has been revealed that shock veins and melt pockets are largely the result of localized stress and temperature concentrations at the interfaces of mineral grains of distinctly different shock impedance, and this effect is most pronounced at metal-silicate and metal pore space interfaces (e.g., Stöffler et al. 1991). However, shock veins are quite common in metal-free shocked rocks, and these features can form readily in meteorites that lack metal and pores. Therefore, the effect of jetting, which is caused by open fractures or pore space in combination with frictional melting due to shearing was proposed by Kieffer (1977) for the formation of shock veins. Stöffler et al. (1991) pointed out that shock veins are essentially formed by frictional melting, in analogy to the formation of micro-pseudotachylitic breccia in shocked rocks of terrestrial impact craters. Spray (1998) also claimed that hypervelocity impact can cause localized shock- and friction-induced melting in meteorites.

The determination of the cosmogenic nuclides and the ^{81}Kr-Kr dating have indicated that the Suizhou meteorite has an average cosmic-ray exposure age of 30.8 ± 3.3 Ma, implying that the parent body of the Suizhou meteorite experienced a collision event at about 31 Ma ago (Wang and Li 1990). However, this may not be the event that caused the formation of high-pressure phase-bearing melt veins in this meteorite. It seems possible that the melt veins in the Suizhou meteorite were formed in an earlier event, perhaps the major event about 470 Ma ago that affected about two-thirds of the L chondrites (Nesvorny et al. 2009).

Our previous studies revealed that the unmelted portion of the Suizhou chondrite experienced average shock pressure and temperature of about 22 GPa and 1000 °C on the basis of transformation of most plagioclase grains into maskelynite, and the locally developed shock veins in Suizhou were formed at pressures of 22 to 24 GPa that is close to the shock pressure experienced by the Suizhou unmelted chondritic rock but at an elevated temperature of about 1900–2000 °C (Xie et al. 2001; Chen et al. 2004). In order to answer the question of what was the additional heat source for the Suizhou shock veins, we observed a few diagonal melt veins in between two main parallel shock veins (Fig. 8), in addition to the long shock veins shown in Fig. 2 where the oblique shock vein is connected to the top of a major shock vein at an intersection angle of about 45°. These distinct morphological features provide strong and direct evidence for a shearing origin of shock melt veins in the Suizhou meteorite. Hence, we assume that the higher temperature in melt veins than that in the unmelted Suizhou chondritic rock was achieved by localized shear stress excursions caused by the collision event.

It has been found that the cooling rate of the shock veins in meteorites is one of the main factors that control the formation and preservation of shock-produced high-pressure polymorphs in veins (Chen et al. 1998), as the hot melt veins are embedded in comparatively cool unmelted chondritic material and the heat diffusion coefficient of the chondritic mass is extremely low. Langenhorst and Poirier (2000) claimed that the thickness of the vein exerts an important control on cooling. According to their estimation, cooling and solidifying a 1 mm wide vein would require a time period eight orders of magnitude longer than that for a 1 μm wide vein. Therefore, the thinner a shock melt vein, the greater the cooling rate of the vein, and the more species of shock-produced high-pressure polymorphs could be preserved in veins. The cooling rate R for metal in the Suizhou melt veins in the interval 1350–950 °C has been estimated at 10^7 °C s^{-1} using the equation $R = 530{,}000d^{-2.9}$ proposed by Scott (1982), where d is the spacing (in μm) between secondary metal dendrite arms or the width of elongated metal cells. This calculated cooling rate is at least three to four orders of magnitude higher than that in the Sixiangkou and Peace River chondrites (Chen et al. 1998), and five orders of magnitude higher than that in the Ramsdorf and Rose City chondrites (Scott 1982). Hence, we assume that this is the reason why as many as 11 shock-produced high-pressure minerals could be preserved in the Suizhou shock melt veins.

CONCLUSIONS

1. The shock-produced melt veins in the Suizhou meteorite morphologically are the simplest, straightest, and thinnest among all known shock-vein-bearing meteorites.
2. The narrow, fracture-like features in the Suizhou meteorite are shock-induced solid melt veins of chondritic composition and consist of fully crystalline materials without glassy material.
3. The Suizhou shock veins contain more high-pressure mineral species than any other known vein-bearing chondrite. All rock-forming and almost all accessory oxide and phosphate minerals in the Suizhou shock veins were transformed to their high-pressure polymorphs, and no fragments of the precursor minerals were observed in veins. Among the 11 high-pressure mineral phases identified in the Suizhou veins, three are new high-pressure minerals, namely, tuite, xieite, and the CF phase.
4. The specific morphological features imply a shearing origin for the shock veins in the Suizhou meteorite. The higher temperature in melt veins than that in the unmelted Suizhou chondritic rock was achieved by localized shear-friction stress caused by the collision event; and the fast cooling of the extremely thin shock veins is the main reason that up to 11 high-pressure mineral phases remain preserved in veins.

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