Acta Geochim (2025) 44:1059–1073
https://doi.org/10.1007/s11631-025-00774-x

REVIEW ARTICLE

The Suizhou meteorite: A treasure trove of high-pressure minerals

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Received: 25 February 2025 / Revised: 6 March 2025 / Accepted: 12 March 2025 / Published online: 9 April 2025

Abstract The Suizhou meteorite is a heavily shock-metamorphosed L6 chondrite which contains thin shock melt veins. So far, 26 high-pressure phases have been identified from the meteorite. Among the high-pressure phases, ten of them were approved as new minerals which include tuite, xieite, wangdaodeite, chenmingite, hemleyite, poirierite, asimowite, hiroseite, elgoresyite, and ohtaniite, by the Commission on New Minerals, Nomenclature and Classification of the International Mineralogical Association. Other high-pressure phases identified from the meteorite are ahrensite, akimotoite, bridgmanite, lingunite, magnesiowüstite, majorite, majorite–pyrope$_{ss}$, maskelynite, riesite, ringwoodite, wadsleyite, and 5 other phases including phase A, vitrified phase B and phase C, phase D (Ca-rich majorite), and partly inverted ringwoodite. The occurrence and abundance of high-pressure phases makes this meteorite the one with the richest variety of high-pressure minerals to date.

Keywords Suizhou meteorite · Chondrite · Shock melt vein · Phase transition · High-pressure mineral

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1 Introduction

Most of the high-pressure minerals are present in the Earth's deep mantle, but this makes it impossible to collect such minerals. The maximum depth attainable by deep borehole drilling is only ~12 km (Fuchs et al. 1990). In rare cases, a few high-pressure minerals were observed as tiny inclusions in diamond from kimberlite tubes (Moore and Gurney 1985; Tschauner et al. 2020), or in lherzolite xenoliths within mantle rocks (Xie et al. 1990; Collerson et al. 2000). Meanwhile, natural high-pressure minerals have been found mostly in extraterrestrial materials, namely, in shocked meteorites (Xie et al. 2001a, 2001b; Xie and Chen 2016; Chen and Xie 2000; Tomioka and Miyahara 2017; Miyahara et al. 2021) and impact craters (Chao et al 1960, 1962; Xie 1973; Chao and Xie 1989, 1990; Chen et al. 2010a, 2010b, 2019). It has been discovered that the L6 chondrites, such as Suizhou, Sixiangkou, Tenham, and Peace River, and the Martian meteorites, such as Tissint, Shergotty, and Zagami, contain abundant high-pressure phases (Xie et al. 2023; Chen et al. 1996; Ma et al. 2018, 2019a, 2019b).

The Suizhou meteorite is an L6 chondrite, and fell on April 15, 1986, at Dayanpo, Suizhou City, Hubei Province, China. The meteorite consists of olivine, low-Ca pyroxene, diopside, plagioclase, FeNi-metal, troilite, merrillite, chlorapatite, chromite, ilmenite, pyrophanite, native copper, and shenzhuangite (Xie et al. 2001a, 2011b; Xie and Chen 2016; Bindi and Xie 2018). The shock classification of the meteorite is S5 and an extensive transformation of plagioclase to maskelynite has been identified (Xie et al. 2001a; 2011a).

This meteorite contains a few very thin shock-produced melt veins of 100–300 μm in width (Fig. 1), and up to 26 high-pressure phases have been identified within or adjacent to the melt veins. These high-pressure phases belong to two assemblages (Chen et al. 1996; Xie et al. 2000). One is

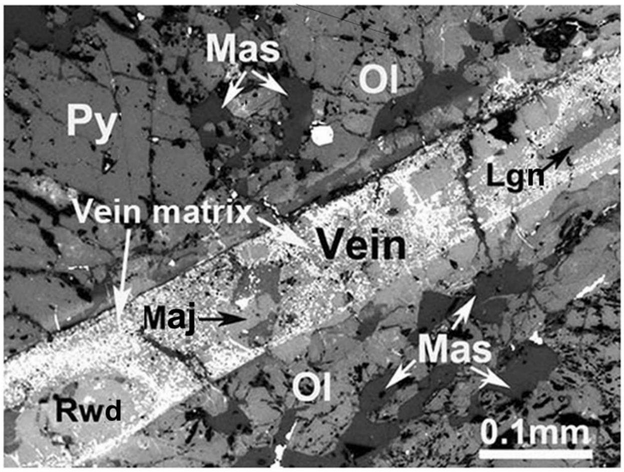

Fig. 1 Back-scattered electron (BSE) image showing a shock melt vein in the Suizhou meteorite. Note this vein is composed of coarse-grained high-pressure minerals ringwoodite (*Rwd*), majorite (*Maj*), and lingunite (*Lgn*), and fine-grained vein matrix. *Ol* olivine, *Py* pyroxene, *Mas* maskelynite

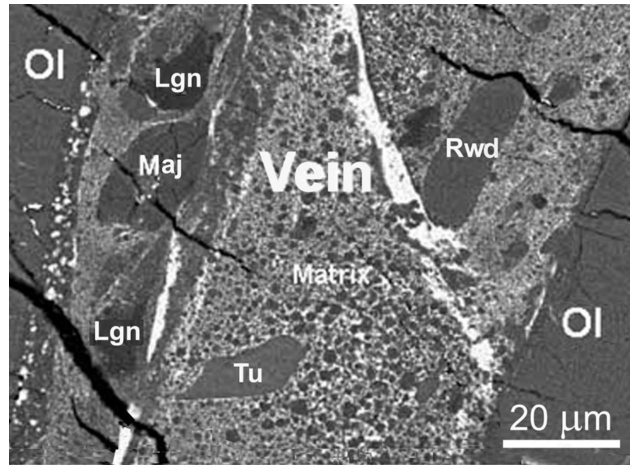

Fig. 2 Back-scattered electron image of a Suizhou shock melt vein showing the occurrence of high-pressure minerals of ringwoodite (*Rwd*), majorite (*Maj*), lingunite (*Lgn*), and tuite (*Tu*). *Ol.* olivine (after Xie et al. 2002a, 2002b)

a coarse-grained mineral assemblage formed through solid-state phase transition, in which the produced high-pressure minerals include ringwoodite, wadsleyite, poirierite, elgoresyite, asimowite, ahrensite, majorite, akimotoite, bridgmanite, ohtaniite, hemleyite, hiroseite, lingunite, tuite, xieite, chenmingite, wangdaodeite, riesite (TiO_2-II), orthorhombic (Ca,Mg)-perovskite, vetrified (Mg,Ca,Fe)SiO_3-perovskite, vetrified (Mg,Ca)SiO_3 perovskite, and (Mg,Ca)SiO_3-majorite. The other is a fine-grained mineral assemblage (vein matrix) crystallized from shock-induced dense melt, in which the produced high-pressure minerals include majorite-pyrope, magnesiowüstite, cryptocrystalline ringwoodite, and partly inverted ringwoodite (Xie and Chen 2016; Xie and Gu 2023; Xie et al. 2001a, 2001b, 2002a, 2002b, 2003, 2011a, 2011b, 2016a, 2016b, 2020, 2023; Chen and Xie 2015; Chen et al. 2003a, 2003b, 2008; Bindi et al. 2017, 2019, 2020, 2021, 2024; Ma et al. 2018, 2019a, 2019b; Tomioka and Miyahara 2017; Tschauner et al. 2020; Tomioka et al. 2021). Among the coarse-grained high-pressure minerals, ten of them have been approved as new minerals by the Commission on New Minerals, Nomenclature and Classification (CNMNC). High-pressure phase transitions in silicate, oxide, and phosphate minerals have been observed in the Suizhou meteorite. This paper reviews the occurrences of high-pressure phases in this meteorite.

2 High-pressure minerals formed through solid-state transition

2.1 High-pressure polymorphs of (Mg,Fe)$_2$SiO$_4$ forsterite

Olivine, (Mg,Fe)$_2$SiO$_4$, is one of the major constituents in chondritic meteorites. In the Suizhou meteorite, the high-pressure polymorphs of olivine (forsterite, α-phase) include wadsleyite (β-phase), ringwoodite (γ-phase), and poirierite (*ε*-phase).

2.1.1 Ringwoodite

Natural γ-(Mg,Fe)$_2$SiO$_4$ is a spinel-structured polymorph of olivine. It was first reported by Binns et al. (1969) within black shock veins in the Tenham L6 chondrite, and was named as ringwoodite after the name of Australian petrologist, A. E. Ringwood. The Suizhou polycrystalline grains of ringwoodite of 10–50 µm in length are smooth, rounded, and unfractured. They occur within the shock melt veins of this meteorite (Fig. 2). The ringwoodite grains have the same chemical composition as olivine in unmelted chondritic rock (Xie and Chen 2016). This indicates that these ringwoodite grains must have formed directly from olivine through solid-state phase transformation under high pressures.

2.1.2 Wadsleyite

Natural *β*-(Mg,Fe)$_2$SiO$_4$ is a spinelloid-type polymorph of olivine. It was firstly discovered in the shock veins of the Tenham and Peace River L6 chondrites (Putnis and Price 1979). This high-pressure silicate mineral was named wadsleyite, after A. D. Wadsley. by Price et al. (1983). In the Suizhou meteorite, Fe-poor (FeO up to 1.50 wt%) and Fe-rich (FeO up to 6.0 wt%) wadsleyites were observed in its shock melt veins (Bindi et al. 2024). They occur in association with ohtaniite, $MgSiO_3$ glass and FeNi metal (Fig. 3). X-ray diffraction analyses have revealed that both Fe-poor and Fe-rich wadsleyite exhibit the classic features observed in the crystal structure of normal wadsleyite.

2.1.3 Poirierite

The presence of ε-$(Mg,Fe)_2SiO_4$, a high-pressure polymorph of olivine with a structure intermediate between olivine, ringwoodite, and wadsleyite, was theoretically predicted by Madon and Poirier (1983). Natural ε-$(Mg,Fe)_2SiO_4$ was first found in the shock melt veins of the Suizhou, Tenham, and Miami L6 chondrites by Tomioka et al. (2021). In the Tenham meteorite, this ε-phase occurs as nanoscale lamellae coherently intergrown in ringwoodite grains. In the Suizhou meteorite, it occurs as tiny grains and veinlets within ringwoodite grains (Fig. 4). This ε-$(Mg,Fe)_2SiO_4$ was named poirierite after Dr. Jean-Paul Poirier, in honor of his contributions to mineral physics, including the theoretical prediction of the ε-Mg_2SiO_4 phase. It was proposed that poirierite was formed during rapid decompression at relatively low temperature in retrograde shock metamorphism of these meteorites.

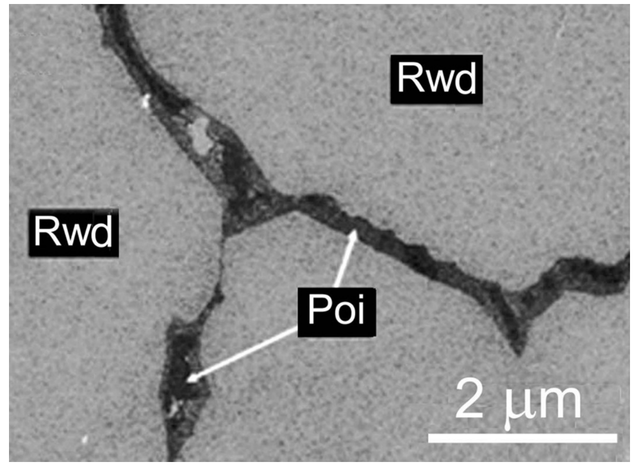

Fig. 4 BSE image showing the occurrence of poirierite (*Poi*) coexisting with ringwoodite (*Rwd*) taken from a shock vein of the Suizhou meteorite

2.2 A special high-pressure (Mg,Fe)-silicate—elgoresyite

A high-pressure polymorph of other (Fe,Mg)-silicate with the composition $(Mg,Fe)_5Si_2O_9$ was discovered in a shock melt vein of the Suizhou meteorite, and was named elgoresyite after A. El Goresy (Bindi et al. 2021). It occurs as a very rare, subhedral µm-sized crystal closely associated with ringwoodite, taenite, in a $MgSiO_3$ glass (Fig. 5). The crystal structure of this (Fe,Mg)-silicate is the same as the iron oxide, Fe_7O_9, strongly suggesting that silicates also form the $[(Mg,Fe)O]_{m+n}(SiO_2)_n$ series which are isostructural to iron oxides via $(Mg^{2+}, Fe^{2+}) + Si^{4+} = 2Fe^{3+}$ substitution. This (Fe,Mg)-silicate is thought to be a potential constituent mineral in rocky planets with relatively high MgO + FeO content.

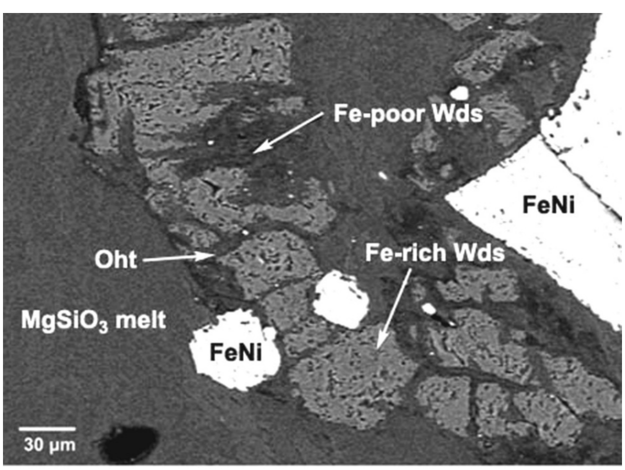

Fig. 3 BSE image showing the occurrence of Fe-rich and Fe-poor wadsleyites (*Wds*) in a Suizhou shock melt vein. *Oht.* ohtaniite, *FeNi.* FeNi metal (after Bindi et al. 2024)

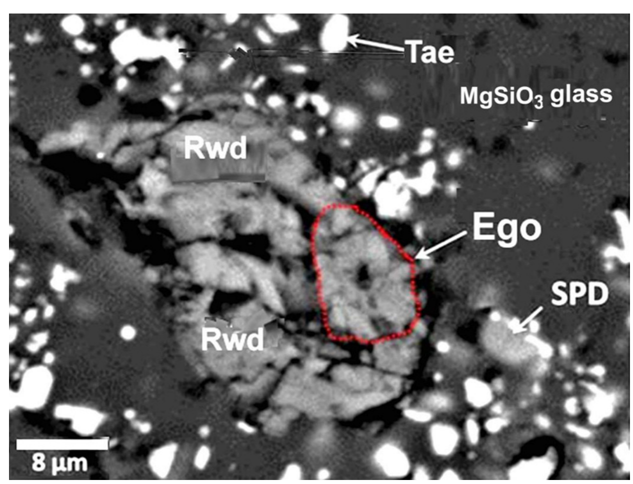

Fig. 5 BSE image showing the occurrence of elgoresyite (*Ego*), indicated with the *dotted red line*, which is associated with ringwoodite (*Rwd*) and a spenelloid silicate (*SPD*; Ma et al 2019b) within $MgSiO_3$ glass (after Bindi et al. 2021)

2.3 High-pressure polymorphs of $(Fe,Mg)_2SiO_4$ fayalite

The high-pressure polymorphs of fayalite (α-phase) include asimowite (β-phase,) and ahrensite (γ-phase). Both asimowite and ahrenside were discovered within a shock melt vein of the Suizhou meteorite (Bindi et al. 2019, 2020).

2.3.1 Ahrensite

The silicate, γ-Fe_2SiO_4 phase, is the spinel-structured polymorph of fayalite. Natural γ-Fe_2SiO_4 was discovered in the shock-melt vein of the Umbarger L6 ordinary chondrite (Xie et al. 2002a, 2002b). It was also observed in the melt-pocket of the Tissint Martian meteorite and named ahrensite after T. Ahrens (Ma et al. 2016). In the Suizhou meteorite, ahrensite occurs as solid-solution grains with ringwoodite within its shock melt veins (Bindi et al. 2020). Ahrensite in this solid solution has the composition of $(Fe^{2+}{}_{0.91}Mg_{0.85}Al_{0.06}Ca_{0.06}Na_{0.05})Si_{1.01}O_4$. This solid solution exhibits the normal spinel structure, with Fe(Mg) in the octahedral A site and Si in the tetrahedral B site. Its associate minerals are Fe-bearing periclase, hiroseite, and $MgSiO_3$ glass (Fig. 6).

2.3.2 Asimowite

The silicate β-Fe_2SiO_4 phase is the spinelloid-structured polymorph of fayalite. The natural β-Fe_2SiO_4, a mineral with Fe dominance over Mg in the octahedral sites, was found as inclusions in the shock-induced FeNi droplets of the Suizhou meteorite and the Quebrada Chimborazo 001 CB carbonaceous chondrite, and was named asimowite after P. D. Asimow (Bindi et al. 2019). Asimowite is also found in the Suizhou meteorite as round inclisions in FeNi metal (Fig. 7) and it is chemically homogeneous, and its empirical formula is $(Fe^{2+}{}_{1.10}Mg_{0.80}Cr^{3+}{}_{0.04}Mn^{2+}{}_{0.02}Ca_{0.02}Al_{0.02}Na_{0.01})_{\Sigma=2.01}(Si_{0.97}Al_{0.03})_{\Sigma=1.00}O_4$ (Fig. 7).

2.4 High-pressure polymorphs of $(Mg,Fe)SiO_3$ orthopyroxene

At high pressure and temperature, low-calcium (Mg,Fe) SiO_3 orthopyroxene transforms to high-pressure polymorphs including majorite, akimotoite, perovskite (bridgmanite), and ohtaniite, an unusual Mg–silicate of $MgSiO_3$ composition, but with an Mg_2SiO_4 wadsleyite structure. The spatial relationship between the composed grains of pyroxene, akimotoite, and vitrified perovskite was observed in the Suizhou meteorite (Fig. 8), which demonstrates a temperature gradient from the shock melt vein to the chondritic portion.

2.4.1 Majorite

Majorite is the high-pressure polymorph of low-calcium pyroxene $(Mg,Fe)SiO_3$ with a garnet structure. The first natural occurrence of majorite within a veinlet in the Coorara meteorite was reported by Smith and Mason (1970), and was named majorite after the name of Australian petrologist, A. Major. Polycrystalline grains of majorite occur in the shock melt veins of the Suizhou meteorite with the grain sizes ranging from 8 to 50 μm in diameter (Figs. 2, 9). These grains are also smooth and unfractured. Electron microprobe analyses show that the Suizhou majorite has the same chemical composition as the low-Ca pyroxene outside the veins, indicating that the Suizhou majorite is formed from low-Ca

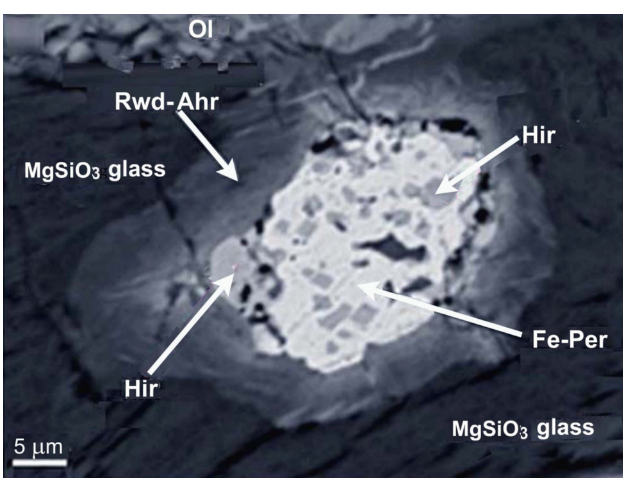

Fig. 6 BSE image showing the occurrence of ringwoodite/ahrensite (*Rwd/Ahr*) solid solusion which is associated with Fe-periclase (*Fe-Per*), hiroseite (*Hir*), olivine (*Ol*), and $MgSiO_3$ glass in a Suizhou shock vein (after Bindi et al. 2019)

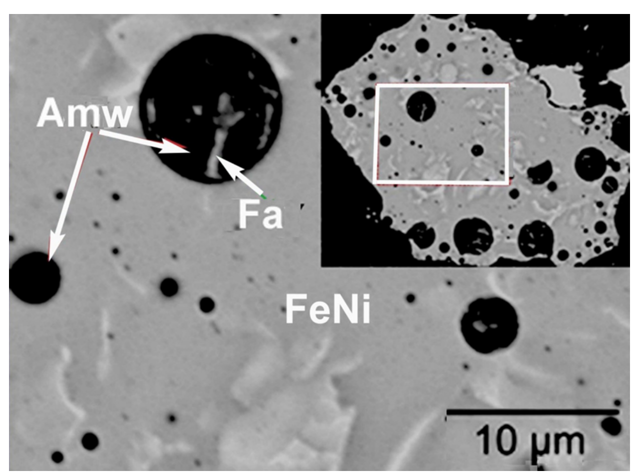

Fig. 7 BSE image showing the occurrence of asimowite (*Amw*) droplets withn FeNi metal in the Suizhou meteorite. *Fa.* fayalite, *FeNi.* FeNi metal (after Bindi et al. 2019)

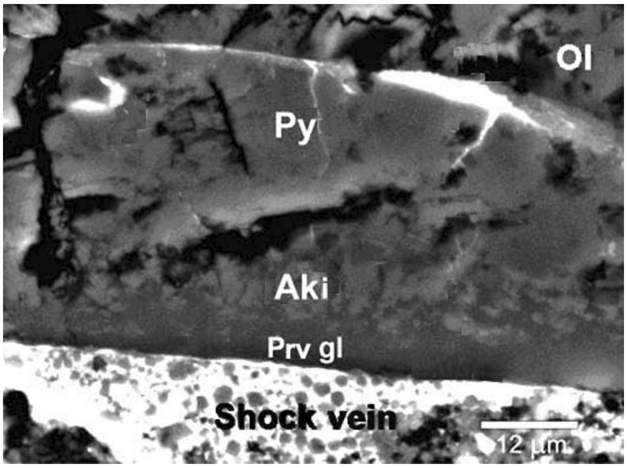

Fig. 8 BSE image showing the zonal akimotoite (*Aki*) in between pyroxene (*Py*) and (Mg,Fe)SiO_3-perovskite glass (*Prv gl*) in the Suizhou meteorite. The (Mg,Fe)SiO_3-perovskite glass is in direct contact with shock vein. *Olv.* olivine (after Chen and Xie 2004)

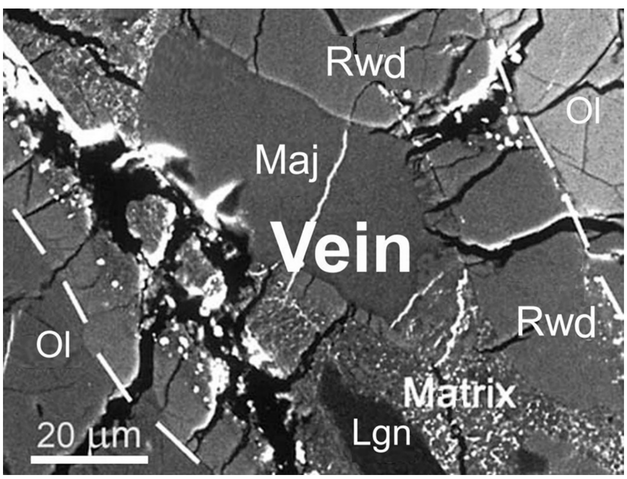

Fig. 9 BSE image showing the occurrence of majorite (*Maj*) in the shock melt vein of Suizhou meteorite. *Rwd.* ringwoodite, *Lgn.* lingunite, *Ol.* olivine. (after Xie and Chen 2016)

pyroxene through solid-state phase transition under high pressures (Xie and Chen 2016).

2.4.2 Akimotoite

Akimotoite is the high-pressure polymorph of low-calcium pyroxene (Mg,Fe)SiO_3 with ilmenite structure. Natural (Mg,Fe)SiO_3-ilmenite was found in the Acfer 040 (L5-6) chondrite (Sharp et al. 1997), and then approved as a new mineral with the mineral name akimotoite (Tomioka and Fujino 1999). Shock-produced akimotoite was also identified in the Suizhou meteorite, which occurs in two kinds (Chen and Xie 2015). The first is the zonal polycrystalline aggregates of akimotoite in shocked pyroxene grains close to the shock vein, where akimotoite occurs in a zonal area in between pyroxene and $MgSiO_3$-glass as irregular small clumps up to 5 μm in size (Fig. 8). The second is the irregular layers of akimotoite up to 4 μm in thickness occurring in fractures and cracks of low-Ca pyroxene enclosed in the shock veins (Fig. 10). This occurrence suggests a solid-state transformation mechanism of pyroxene to akimotoite, and that akimotoite should have nucleated, and grew in the area with abundant defects caused by shock deformation because the defect significantly enhances the solid-state reactivity and the kinetics of nucleation of high-pressure phase (Chen and Xie 2015).

2.4.3 Vitrified perovskite (bridgmanite)

The natural perovskite-structured (Mg,Fe)SiO_3 phase with an orthorhombic symmetry was first identified in the Tenham L6 ordinary chondrite (Tomioka and Fujino 1999). A fine-grained assemblage of amorphous (Mg,Fe)SiO_3 phase plus akimotoite was found in the shock vein matrix of the Acfer 040 meteorite (Sharp et al. 1997). Fine-scale intergrowth of (Mg,Fe)SiO_3-perovskite and magnesiowüstite, as post-ringwoodite dissociation products of olivine, were also found in the shergottite DaG 735 (Miyahara et al. 2011a, 2011b). The mineral was named bridgmanite after P. W. Bridgman (Tschauner et al. 2014). The vitrified (Mg,Fe) SiO_3 perovskite phase was observed in shock melt veins of the Suizhou meteorite (Chen et al. 2004). The ovoid grains of this phase are closely associated with ringwoodite and majorite and surrounded by a fine-grained vein matrix composed of majorite-pyrope garnet, ringwoodite, magnesiowüstite, metal, and troilite (Fig. 11). Heating experiments

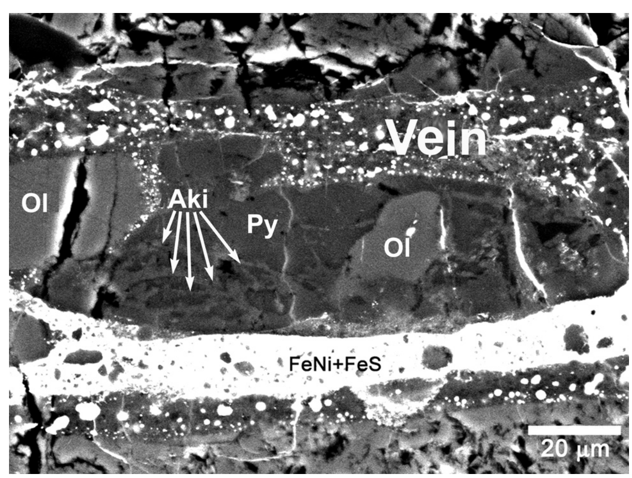

Fig. 10 BSE image showing an ovoid fragment of chondritic rock in the Suizhou shock vein. Note the occurrence of akimotoite (*Aki*) along fractures and cracks inside a low-Ca pyroxene (*Py*) fragment. *Ol.* olivine (after Chen and Xie 2015)

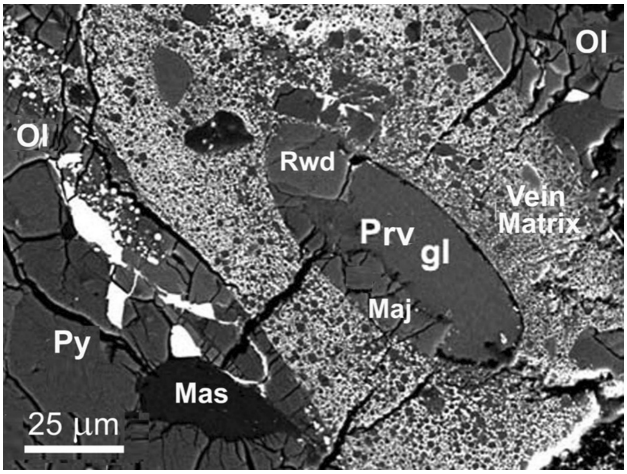

Fig. 11 BSE image showing the occurrence of glassy perovskite (*Prv gl*) in a shock vein of the Suizhou meteorite. *Rwd.* ringwoodite, *Maj.* majorite, *Mas.* maskelynite, *Ol.* olivine, *Py.* pyroxene

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 (Durben and Wolf 2008; Hemmati et al. 1995). Hence, the formation of vitrified $(Mg,Fe)SiO_3$ in the Suizhou shock veins is interpreted to have amorphized from perovskite after pressure release (Chen et al. 2004).

2.4.4 Ohtaniite

The natural high-pressure silicate phase with a composition close to that of a pyroxene but with wadsleyite structure was discovered in a shock melt pocket of the Suizhou meteorite, and named ohtaniite in honor of Eiji Ohtani (Bindi et al. 2024). This unusual mineral occurs as tiny irregular grains in the $MgSiO_3$ melt, and is associated with Fe-poor and Fe-rich wadsleyite and FeNi metal (Fig. 12). Electron microprobe analyses of this mineral gave the empirical formula (based on 8 oxygen atoms pfu) $[(Mg_{2.73}Fe^{2+}{}_{0.14}Na_{0.03}Al_{0.03}Ca_{0.02}Si_{0.05})_{\Sigma3.00}(Si_{0.49}\square_{0.51})_{\Sigma1.00}]Si_2O_8$, ideally $Mg_3(Si_{0.5}\square_{0.5})Si_2O_8$. Single-crystal X-ray studies showed the mineral to be orthorhombic, space group *Imma* (#74), with the unit-cell parameters: $a = 5.5820(10)$, $b = 11.418(3)$, $c = 7.708(2)$ Å, $V = 491.3(2)$ Å3, and $Z = 4$. $a = 5.5820(10)$, $b = 11.418(3)$, $c = 7.708(2)$ Å, $V = 491.3(2)$ Å3, and $Z = 4$. This indicates that ohtaniite has the structure of wandsleyite, a polymorph of Mg_2SiO_4 olivine. Hence, the finding of ohtaniite expands our understanding of shock-induced mineralogical transformations in extraterrestrial materials.

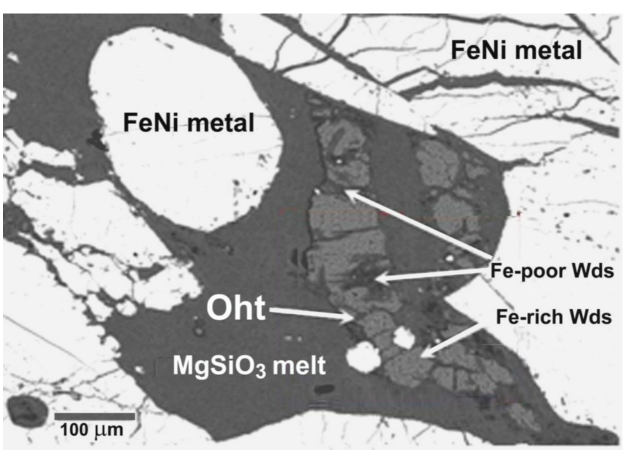

Fig. 12 BSE image showing the occurrence of ohtaniite in a Suizhou shock melt pocket. *Wds.* wadsleyite (after Bindi et al. 2024)

2.5 High-pressure polymorphs of $(Fe,Mg)SiO_3$ ferrosilite

At high pressure and high temperature, the $(Fe,Mg)SiO_3$ ferrosilite transforms to ilmenite-structured hemleyite and perovskite-structured hiroseite. Both these high-pressure minerals have been discovered for the first time in shock melt veins of the Suizhou meteorite (Bindi et al. 2017, 2020).

2.5.1 Hemleyite

The natural ilmenite-structured $(Fe,Mg)SiO_3$ phase with Fe/(Mg + Fe) = 0.56 was discovered in an unmelted portion of the shocked Suizhou meteorite (Fig. 13). The mineral was named hemleyite after R. J. Hemley (Bindi et al. 2017). It was associated with olivine, Fe-rich clinoenstatite, and surrounded by Fe-poor clinoenstatite, which implies that the

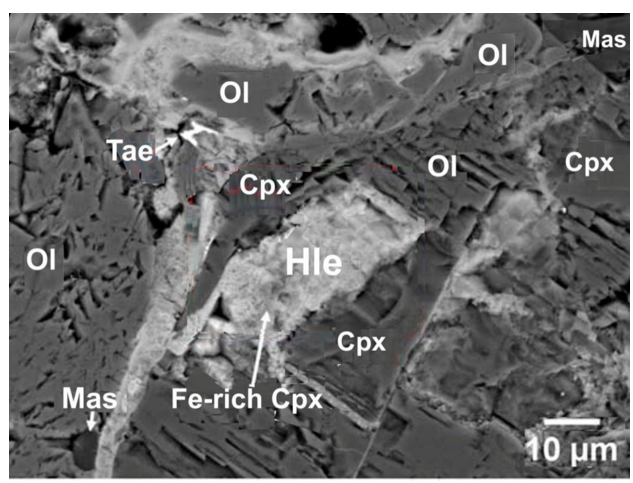

Fig. 13 BSE image showing the occurrence of hemleyite (*Hle*) in the Suizhou meteorite. *Ol.* olivine, *Cpx.* clinopyroxene, *Mas.* maskelynite, *Tae.* taenite (after Bindi et al. 2017)

Fe-rich clinoenstatite belongs to a kind of secondary pyroxene likely formed from olivine and pyroxene by replacement of Fe-rich materials during the thermal metamorphism of the meteorite.

2.5.2 Hiroseite

The natural perovskite-structured polymorph of (Fe,Mg)SiO_3 phase with Fe/(Mg + Fe) = 0.59 was discovered in the shock melt veins of the Suizhou meteorite (Bindi et al. 2020). It occurs as tiny grains within Fe-periclase which is surrounded by a solid solution of ringwoodite and ahrensite and $MgSiO_3$ glass (Fig. 6). The mineral was named hiroseite after K. Hirose. It has been revealed that this crystalline Fe-rich bridgmanite with a $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ ratio of 0.1–0.2 is coexisting with nanocrystalline metallic iron. Thus providing the first evidence for a subsolidus charge disproportionation reaction in natural high-pressure minerals: $3Fe^{2+} \rightarrow Fe^{o} + 2Fe^{3+}$ (Bindi et al 2020).

2.6 High-pressure polymorphs from breakdown of diopside

Diopside is a monoclinic pyroxene mineral of $CaMgSi_2O_6$ composition The results of many experiments performed on diopside at pressure ranges of 18–50 GPa and 1000–1900 °C showed that the diopside had finely broken down into cubic $CaSiO_3$–perovskite and orthorhombic $MgSiO_3$–perovskite, and one of the intermediate products is (Mg,Ca)SiO_3 garnet, the Ca-rich Mg-majorite (Xie and Gu 2023). Fortunately, a shock-metamorphosed diopside grain associated with ringwoodite and lingunite was found in a shock melt vein of the Suizhou meteorite (Fig. 14). The chemical formation of this shock-metamorphosed diopside is $(Ca_{0.419}Mg_{0.466}Fe_{0.088}Ti_{0.007}Cr_{0.018}Na_{0.024})_{1.022}(Si_{0.977}Al_{0.014})_{0.991}$. The detailed micro-mineralogical analyses revealed four high-pressure silicate phases with different compositions and structures within this diopside grain, termed phase A, vitrified phase B and phase C, and phase D (Xie and Gu 2023).

2.6.1 Phase A—the orthorhombic ($Ca_{0.663}$–$Mg_{0.314}$)SiO_3-perovskite

Phase A is the main breakdown product of diopside in the Suizhou melt vein upon shock. It has a rounded shape and gray color with a smooth surface, and is closely associated with phase B (Fig. 15a). Phase A has been identified as orthorhombic perovskite (Xie and Gu 2023), which is different with the cubic $CaSiO_3$-perovskite–davemaoite (Tschauner et al. 2021). The chemical formula of phase A is $(Ca_{0.663}Mg_{0.314})_{0.977}(Si_{0.982}Al_{0.06})_{0.988}O_3$, and its simplified formula is (Ca,Mg)SiO_3. The atom units of Ca in phase A is as twice larger than that of Mg, and phase A does not contain FeO (Xie and Gu 2023).

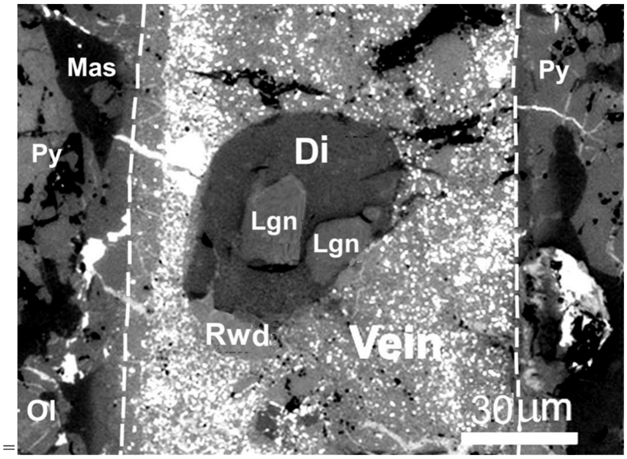

Fig. 14 Photomicrograph showing the shock-metamorphosed diopside (*Di*) grain in a shock melt vein (vein) of the Suizhou meteorite. *Lgn.* lingunite, *Rwd.* ringwoodite, *Ol.* olivine, *Py.* pyroxene, *Mas.* maskelynite (after Xie and Gu 2023)

2.6.2 Vitrified phase B—the ($Mg_{0.642}Ca_{0.290}Fe_{0.098}$)$SiO_3$ perovskite

Phase B is also a main breakdown product of the shocked diopside in the shock melt veins of the Suizhou meteorite. It is of irregular or ladder shape and light color, and occurs around or in the interstices of phase A grains (Xie and Gu 2023). Because of the volume shrinkage during cooling and solidification, some fractures/cracks crosscutting their grains are observed (Fig. 15a). Electron diffraction analysis revealed that phase B is an amorphized phase. The chemical formula of this phase is $(Mg_{0.642}Ca_{0290}Fe_{0.098}Ti_{0.001}Na_{0.024}Cr_{0.005})_{1.060}(Si_{0.967}Al_{0.043})_{1.010}O_3$, and its simplified formula is (Mg,Ca,Fe)SiO_3. FeO content (6.48 wt%) in phase B is a litter higher than diopside (5.40–5.71 wt%) in the chondritic portion of the Suizhou meteorite. Based on the close association of phase B with phase A, and the results of heating experiments of crystalline $MgSiO_3$ perovskite (Durben and Wolf 2008; Hemmati et al. 1995), it has been assumed that phase B is the vitrified $(Mg_{0.642}Ca_{0.290}Fe_{0.098})SiO_3$ perovskite.

2.6.3 Vitrified phase C—the Ca-rich Mg-perovskite with a ($Mg_{0.853}Ca_{0.167}$)SiO_3 composition

Phase C is the third breakdown product of the shock-metamorphosed diopside in the Suizhou meteorite. It has an irregular shape and light gray color. Some volume shrinkage-produced fractures/cracks are also observed (Fig. 15b). Electron diffraction analysis revealed that phase B is also an

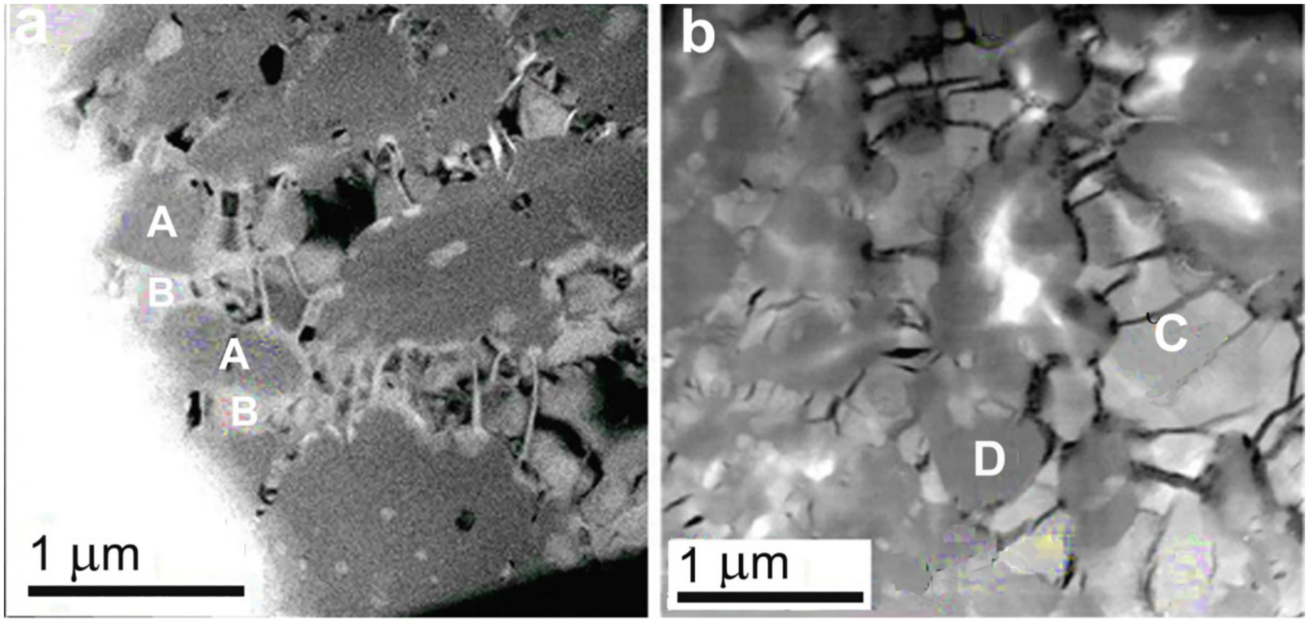

Fig. 15 STEM bright field images of the shock-metamorphosed diopside grain in a shock melt vein of the Suizhou meteorite. a. the occurrence of the coexisting phase A and B; b. the occurrence of phase C and D (after Xie and Gu 2023)

amorphized phase. The chemical formula of the phase C is $(Mg_{0.853}Ca_{0.167}Ti_{0.001}Na_{0.023}Cr_{0.004})_{1.048}(Si_{0.949}Al_{0.041})_{0.990}O_3$, and its simplified formula is $(Mg,Ca)SiO_3$. Although the atom units of Mg in phase C are 5 times larger than those of Ca, the Ca content is still rich enough (CaO = 8.70 wt%), and phase C does not contain FeO (Xie and Gu 2023). It has been identified that phase C in the Suizhou shock-metamorphosed diopside is a vitrified Ca-rich Mg-perovskite with $(Mg_{0.853}Ca_{0.167})SiO_3$ composition.

2.6.4 Phase D—the Ca-rich majorite with $(Mg_{0.578}Ca_{0.414})SiO_3$ composition

Phase D is the fourth breakdown product of shocked diopside in the Suizhou meteorite. It has an irregular or granular shape and dark gray color (Fig. 15b). Phase D grains are commonly surrounded by glassy phase C. The chemical formula of phase D is $(Mg_{0.578}Ca_{0.414}Cr_{0.010})_{1.002}(Si_{0.981}Al_{0.020})_{1.001}O_3$, and its simplified formula is $(Mg,Ca)SiO_3$. The atom unit of Mg in phase D is just a little larger than that of Ca, and phase D does not contain FeO (Xie and Gu 2023). The Raman spectra of phase D spectra can be compared with that of majorite, the $(Mg,Fe)SiO_3$-garnet in the shock melt vein of Suizhou meteorite (Xie et al. 2001a). It has been assumed that the phase D is $(Mg,Ca)SiO_3$ majorite with $(Mg_{0.578}Ca_{0.414})SiO_3$ composition (Xie and Gu 2023).

2.7 High-pressure polymorphs of plagioclase

2.7.1 Lingunite

Hollandite-type $NaAlSi_3O_8$, the high-pressure polymorph of plagioclase, was first discovered in the shock-melt veins of the Sixiangkou chondrite (Gillet et al. 2000), and was named lingunite after L. G. Liu (Liu and El Gorsey 2007). $NaAlSi_3O_8$-hollandite was also identified in the shock melt veins of the Suizhou meteorite (Xie et al. 2001b). Lingunite in the Suizhou meteorite has a dark color and irregular shape, and its grains are smooth and unfractured, with grain sizes ranging from 8 to 25 μm in diameter (Figs. 2, 9, 14). Its chemical composition is similar to that of plagioclase. However, this shock-induced high-pressure phase in veins has slightly higher FeO, MgO, and Na_2O contents and lower K_2O content than those of its host plagioclase.

2.7.2 Maskelynite

The first identification of a dense plagioclase glass is from the shergottite Shergotty and has been called maskelynite after N. S. Maskelyne (Tschermak 1872). This maskelynite has a non-vesicular flow texture resulting from melting and liquid migration followed by solidification. Stöffler et al. (1986) observed some dense plagioclase glass that still retains the morphology of the original plagioclase but loses its crystallinity. Maskelynite has been commonly found in the Suizhou meteorite (Xie et al. 2001a), and both

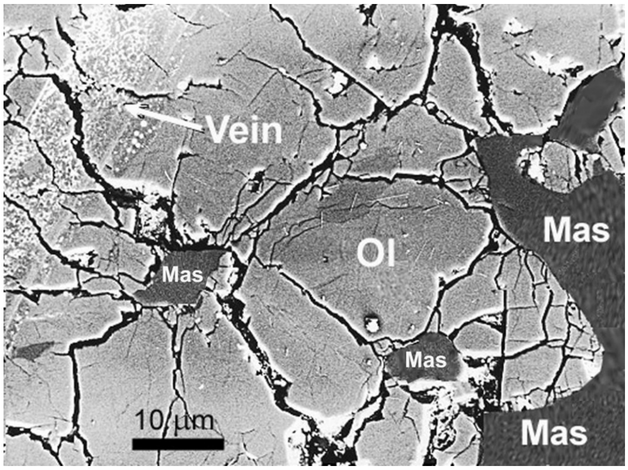

Fig. 16 BSE image showing the two types of occurrence of maskelynie (*Mas*) in the chondritic portion of Suizhou meteorite. One is the large non-vesicular grain with flow texture (*right part of the image*), another is the small grains surrounded by radiating cracks in olivine (*Ol*) Note that these two small grains still retain the morphology of the original plagioclase but lose its crystallinity (after Xie and Chen 2001a)

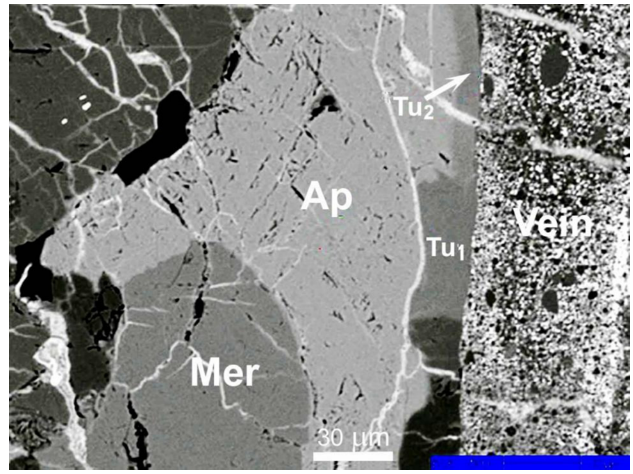

Fig. 17 BSE image showing a composite phosphate grain directly adjacent to the left wall of a Suizhou shock melt vein. Note the dark gray tuite (Tu_1) formed from merrillite (*Mer*), and the gray band of tuite (*Tu_2*) formed from decomposition of chlorapatite (*Ap*). *White lines* penetrating minerals and shock vein are injected FeS veinlets (after Xie et al. 2016a)

types of maskelynite occurrence were observed under a microscope and on BSE images. Figure 16 clearly demonstrates these two occurrence types in the chondritic portion of Suizhou meteorite.

2.8 High-pressure polymorphs of Ca-phosphates

Calcium phosphates are another group of common accessory minerals in meteorites. The most common phosphates in chondrites are merrillite and apatite. It was found that both merrillite and apatite could transform to the high-pressure phase, tuite, under pressure (Xie et al. 2003, 2013).

2.8.1 Tuite transformed in solid state from merrillite

The high-pressure γ-$Ca_3(PO_4)_2$ phase was synthesized by Murayama et al. (1986). The natural γ-$Ca_3(PO_4)_2$ phase transformed in solid state from merrillite was found in the shock melt vein of the Suizhou meteorite (Xie et al. 2002a, 2002b), and was named tuite after G. C. Tu (Xie et al. 2003). Two types of tuite occurrence were observed (Xie et al. 2002a, 2002b, 2016a). The first one is in the form of a single grain with round outline occurring within shock melt veins (Fig. 2). This type of tuite occurs as small polycrystalline grains in association with some other high-pressure mineral in the veins. The other is formed through partial decomposition of merrillite. This type of tuite occurs as a narrow band directly adjacent to the wall of a shock vein (Fig. 17). Tuites of both types contain small contents of Na_2O and MgO, but do not contain Cl.

2.8.2 Tuite formed through decomposition of chlorapatite

Two tuite grains have been identified as a consequence of the high-pressure decomposition of chlorapatite, $2Ca_5(PO_4)_3Cl \rightarrow 3\gamma\text{-}Ca_3(PO_4)_2 + CaCl_2$, in a shock vein of the Suizhou meteorite (Xie et al. 2013). The larger grain measures approximately 20 × 35 µm, and the smaller one approximately 10 × 20 µm (Fig. 18). These two grains do not exhibit fractures and are gray in color under reflected light. In addition, the partial decomposition of chlorapatite makes the second occurrence of tuite in the Suizhou meteorite (Xie

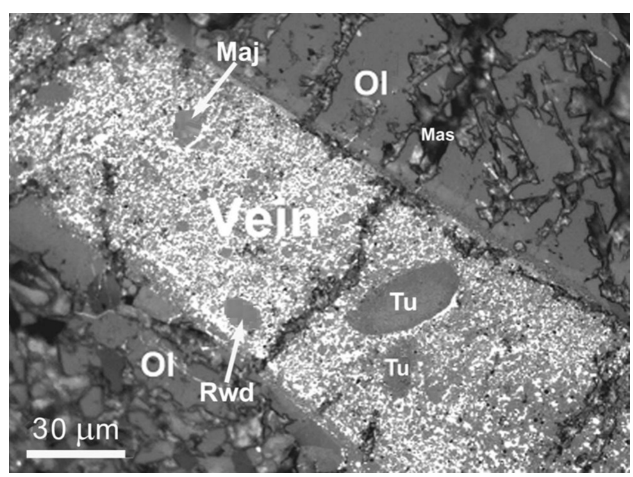

Fig. 18 Reflected light microphotograph showing the two tuite (*Tu*) grains formed from decomposition of chlorapatite in a Suizhou shock melt vein. *Rwd* Ringwoodite, *Maj.* majorite, *Mas.* maskelynite, *Ol.* olivine

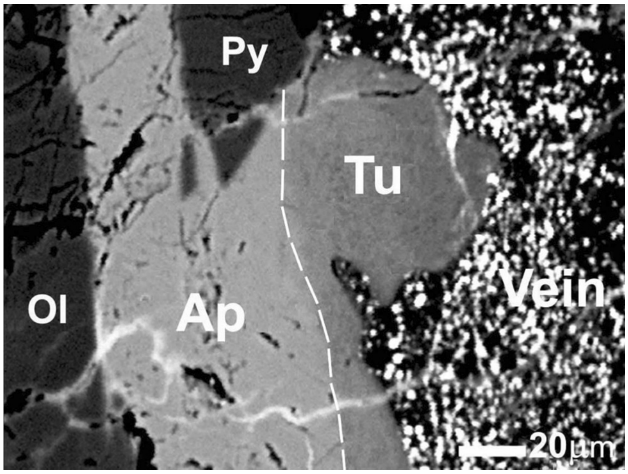

Fig. 19 BSE image showing a chlorapatite (*Ap*) grain partly transformed to tuite (*Tu*) through its decomposition in the area adjacent to a melt vein. *Ol.* olivine, *Py.* pyroxene

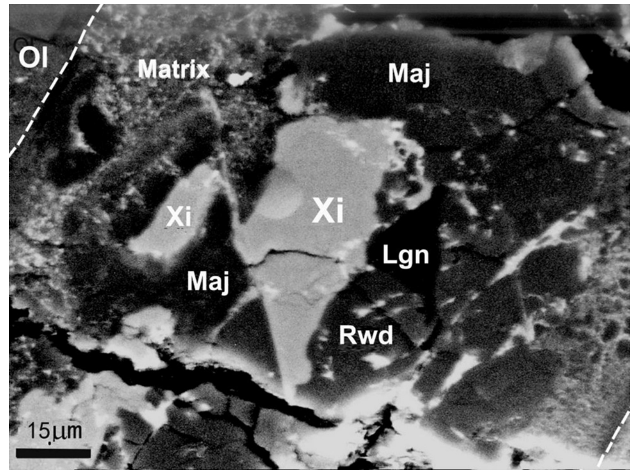

Fig. 20 BSE image showing two xieite (*Xi*) grains surrounded by other high-pressure minerals ringwoodite (*Rwd*), majorite (*Maj*), and lingunite (*Lgn*) in a Suizhou shock melt vein (after Xie and Chen 2016)

et al. 2016a), i.e., as a narrow band or a nodule directly adjacent to the wall of a shock vein (Figs. 17, 19). In opposition to the tuites transformed from merrillite, tuites formed through decomposition of chlorapatite do not contain Na_2O and MgO, but contain a small amount of Cl.

2.9 High-pressure polymorphs of oxides

The main extraterrestrial oxide minerals occurring in meteorites are chromite, ilmenite, and rutile. All these oxide minerals could transform to their high-pressure phases, respectively, by shock-loading. Fortunately, high-pressure polymorphs of these three oxide minerals, namely, xieite, wangdaodeite, and riesite (TiO_2-II) were discovered in the Suizhou meteorite (Chen et al. 2003b; Ma et al. 2019a; Xie et al. 2023).

2.9.1 Xieite

$CaTi_2O_4$-type $FeCr_2O_4$ phase, a postspinel high-pressure polymorph of chromite, was synthesized by Chen et al. (2003a), and natural $CaTi_2O_4$-type $FeCr_2O_4$ phase was discovered in the shock melt veins of the Suizhou meteorite (Chen et al. 2003b). This mineral was named xieite after X. D. Xie (Chen et al. 2008). It occurs in association with other high-pressure minerals including ringwoodite, majorite, and lingunite (Fig. 20). Xieite occurs as compact polycrystalline aggregates of about 5–40 μm in grain size and commonly displays as a pseudomorph of chromite crystals or its fragments (Xie et al. 2011b). The aggregates are composed of crystallites of less than 1 μm in size. The chemical composition of xieite is the same as $FeCr_2O_4$ chromite. The P–T condition for the formation of xieite is estimated to be 18–23 GPa and 1800–1950 °C, respectively.

2.9.2 Chenmingite

The Café$_2$O$_4$-type $FeCr_2O_4$ phase, the second postspinel high-pressure polymorph of chromite, was also synthesized by Chen et al. (2003b). The natural Café$_2$O$_4$-type $FeCr_2O_4$ phase was first discovered within a shock-metamorphosed chromite grain inside the Suizhou meteorite (Chen et al. 2003b). This mineral was then found within a chromite grain of the Tissint Martian meteorite, and named chenmingite after M. Chen (Ma et al. 2019a). Chenmingite in the Suizhou meteorite occurs as lamella-like slices associating with a chromite matrix, where two–three sets of slices are observed (Fig. 21). The high P–T experiments demonstrate that chenmingite is indeed a quenchable polymorph of chromite formed above 12.5 GPa at temperature lower than that for xieite.

2.9.3 Wangdaodeite

The natural lithium-niobate structured phase of ilmenite $FeTiO_3$ was discovered in shock melt veins or in the area adjacent to shock veins of the Suizhou meteorite, and named wangdaodeite after D. D. Wang (Xie et al. 2020). The polycrystalline wangdaodeite occurs as micro-sized granular grains 2–18 μm in size, composed of nanomeritic crystals of 10–80 nm. In contrast to the fractured ilmenite grains outside the veins, no microstructures were observed inside the wangdaodeite grains (Fig. 22). Wangdaodeite is isochemical to and structurally close to its host $FeTiO_3$

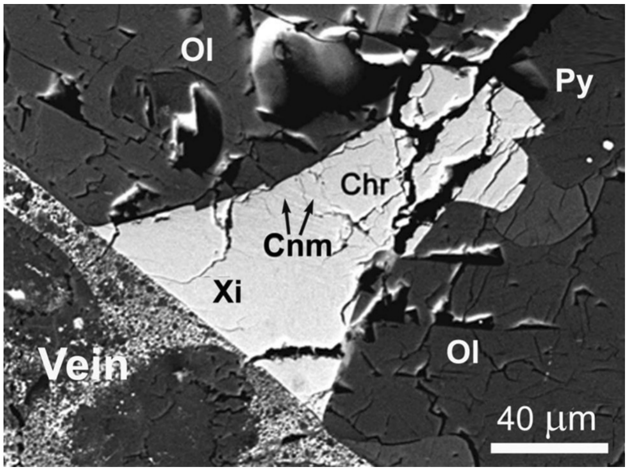

Fig. 21 BSE images showing a shock-metamorphosed chromite-spinel grains. This chromite grain has been transformed to a xieite (*Xi*) zone contacting with shock vein, and partially to a chenmingite (*Cnm*) + chromite zone between the xieite zone and the chromite zone (*Chr*) apart from the shock vein (after Xie and Chen 2016)

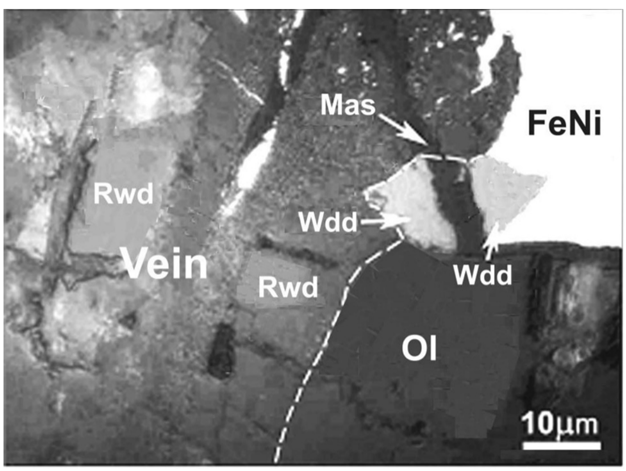

Fig. 22 Photomicrograph showing the occurrence of wangdaodeite (*Wdd*) in the Suizhou meteorite. Note the wangdaodeite grain is partitioned by maskelynite (*Mas*) in contact with a shock vein. *Ol.* olivine, *Rwd.* ringwoodite, *FeNi.* FeNi metal (after Xie et al. 2020)

ilmenite. The essential difference is in space group: wangdaodeite is *R*3*c* and ilmenite is *R*-3. The P–T conditions for formation of wangdaodeite were estimated to be 20–24 GPa and > 1200 °C.

2.9.4 Riesite (TiO_2-II)

Riesite (TiO_2-II) is the α-PbO_2-structured high-pressure phase of rutile. Natural TiO_2-II was previously found in ultrahigh-pressure metamorphic and mantle-derived rocks, and in tektite. This polymorph of rutile was found in the Ries impact crater (El Goresy et al. 2001), and was named riesite after the name of the location (Tschauner et al. 2020). This high-pressure phase was also discovered in the unmelted rock of the shocked Suizhou meteorite (Xie et al. 2023). It occurs as needle- and leaf-shaped inclusions in ilmenite (Fig. 23), as well as a patch- and tape-shaped body in pyrophanite. The P–T regime estimated for the phase transition of rutile into TiO_2-II phase is 20–25 GPa and 1000 °C.

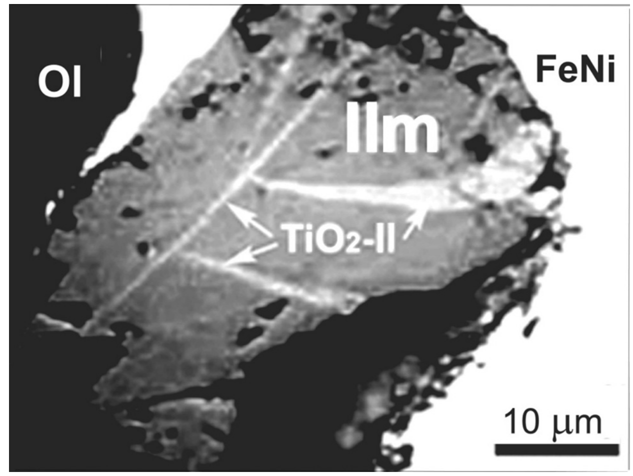

Fig. 23 Reflected light photomicrograph showing the leaf-shaped and needle-like TiO_2-II grains within ilmenite (*IIm*) in the Suizhou meteorite. *Ol.* olivine, *FeNi.* FeNi metal (after Xie et al. 2023)

3 High-pressure minerals crystallized from shock melt in veins

The fine-grained vein matrix in the Suizhou meteorite is composed of euhedral garnet crystals with majorite–pyrope composition and irregular grains of magnesiowüstite, and cryptocrystalline ringwoodite, along with eutectic intergrowths of FeNi metal and troilite in the interstices between garnet crystal (Fig. 24) (Xie et al. 2011a, 2016a, 2016b). In addition, a fine-grained partly inverted ringwoodite of $(Mg,Fe,Si)_2(Si,\square)O_4$ composition was also found in shock veins of the Suizhou meteorite (Ma et al. 2019b).

3.1 Majorite–pyrope garnet

Majorite–pyrope garnet is a major constituent of the Suizhou vein matrix. Most of the idiomorphic garnet crystals had grain size of 1–2 µm, but crystals larger than 6 µm were also observed. Under TEM, the garnet crystals were transparent and no internal microstructures were observed (Fig. 24). In

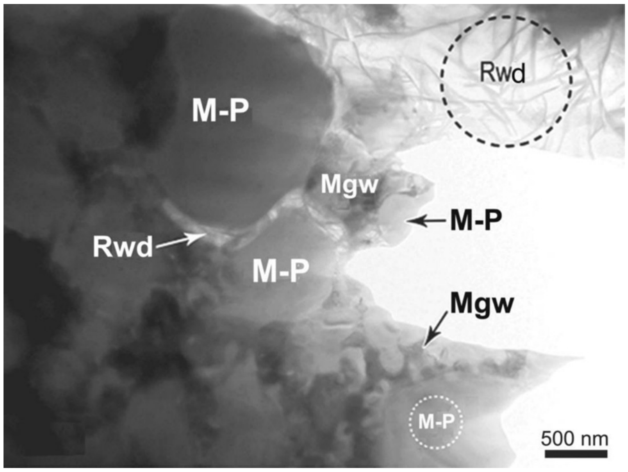

Fig. 24 Bright-field TEM image showing the occurrence of three composed minerals in the Suizhou vein matrix: idiomorphic crystals of majorite–pyrope garnet (*M-P*), irregular grains of magnesiowüstite (*Mgw*) in the interstices of garnets, and cryptocrystalline ringwoodite (*Rwd*) (after Xie and Chen 2016)

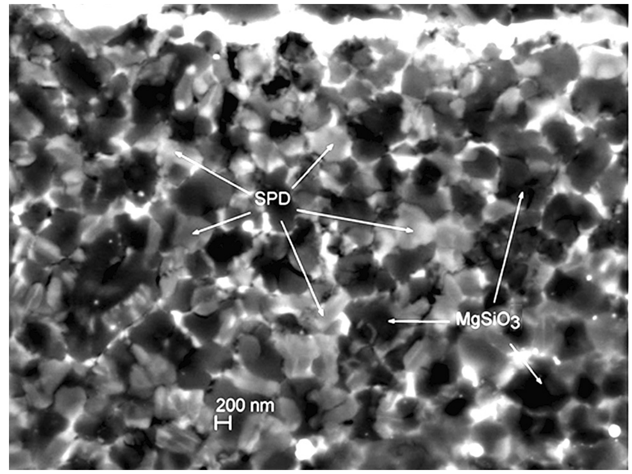

Fig. 25 BSE image showing the fine-grained partly inverted ringwoodite $(Mg,Fe,Si)_2(Si,\square)O_4$ with $(Mg,Fe)SiO_3$ within the matrix of a melt vein in *Ol* olivine, *Rwd* ringwoodite, *FeNi* FeNi metaSuizhou meteorite (after Ma et al. 2019b)

comparison with its precursor pyroxene, the majorite–pyrope garnet showed increased Al_2O_3 and CaO contents. On the basis of its higher Al_2O_3 content (3.51 wt%) than that in pyroxene (0.16 wt%), this garnet mineral was identified as majorite–pyrope in solid solution (Xie et al. 2001a).

3.2 Magnesiowüstite (Fe-rich periclase)

Magnesiowüstite, (Mg,Fe)O, is the second most abundant mineral in the vein matrix of Suizhou meteorite. It has an irregular shape, and fills the interstices between majorite–pyrope garnet crystals, implying that magnesiowüstite crystallized after the solidification of garnet in veins (Xie et al. 2001a). Under TEM, this mineral showed a clear polycrystalline nature (Fig. 24). The diameter of the polycrystalline grains ranged from several tens to several hundred nanometers (Xie et al. 2016a, 2016b). The empiric formula of magnesiowüstite was determined to be Wu_{53}–$Per_{47,}$ where Wu is wüstite and Per is periclase.

3.3 Cryptocrystalline ringwoodite

Cryptocrystalline grains of ringwoodite were observed in the shock melt vein of Suizhou meteorite either in the form of narrow independent bands of 2–3 μm in width, or as irregular grains filling the interstices between garnet crystals or garnet and magnesiowüstite grains (Xie et al. 2001a). Under TEM, this type of ringwoodite appeared transparent, but with many microfractures of different directions probably formed by volume shrinkage during cooling (Fig. 24).

3.4 Partly inverted ringwoodite $(Mg,Fe,Si)_2(Si,\square)O_4$

The fine-grained partly inverted ringwoodite of $(Mg,Fe,Si)_2(Si,\square)O_4$ composition was observed within the matrix of a shock melt vein along with the fine-grained $(Mg,Fe)SiO_3$-phase in the Suizhou meteorite (Ma et al. 2019b). The crystal size is generally in the range of 100–800 nm (Figs. 5, 25). This phase contains 2.23–3.53 wt% of Al_2O_3, 1.09–2.04 wt% of CaO, and 0.85–1.31 wt% of Na_2O, which implies that it crystallized from shock-induced dense silicate melt.

4 Summary

The identification of 26 high-pressure phases in the Suizhou meteorite indicates that this meteorite contains abundant high-pressure minerals in the ordinary chondrites. The abundant production of high-pressure minerals indicates that the impact-triggered temperature and pressure conditions of this meteorite are relatively favorable for the preservation of high-pressure minerals. Among identified 26 high-pressure phases, 11 of them had been previously discovered in other meteorites, 10 of them are new minerals approved by CNMNC of the International Mineralogical Association, and 5 are other phases. The discovery of a large number of different types of high-pressure minerals and phases in the Suizhou meteorite indicates that shock-metamorphosed meteorites are a treasure trove of natural high-pressure minerals.

Acknowledgements This research is supported by Science and Technology Planning Project of Guangdong Province, 2023B1212060048. We are grateful to the reviewers for their constructive comments that helped improve the manuscript.

Authors contributions Xiande Xie conceived the project and supervised the study, acquired funding, interpreted the data, wrote the first version of the manuscript. All authors are discoverers of high-pressure minerals in the Suizhou meteorite and contributed to the writing of the final version of the manuscript.

Funding Science and Technology Planning Project of Guangdong Province (2023B1212060048).

Declarations

Conflict of interest The authors declare that they do not have any known competing financial interest or personal relationship that could have appeared to influence the work reported in this paper.

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