Shock-induced incongruent melting of olivine in Kamargaon L6 chondrite

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Key Points:

- We report shock-induced incongruent melting of olivine in an ordinary chondrite for the first-time
- Olivine first dissociated to magnesiowüstite and liquid followed by crystallization of bridgmanite from the residual liquid
- Olivine grains may have experienced pressure and temperature of ~25 GPa and ~2500 °C

Abstract

Here we report for the first-time shock-induced incongruent melting of olivine in an ordinary chondrite. Several olivine grains (Fo_{74}), entrained in the shock-melt vein of the Kamargaon L6 chondrite were dissociated into magnesiowüstite (X_{Fe} = 0.71) and orthoenstatite (X_{Fe} = 0.22). We propose that the breakdown of olivine took place as a result of incongruent melting to produce magnesiowüstite and Mg-rich liquid. We suggest that bridgmanite may have crystallized as the second phase from the olivine melt which back transformed to a low-pressure phase of orthoenstatite from subsequent high-temperature and low-pressure events. In this case, olivine grains may have experienced pressure and temperature of ~25 GPa and ~2500 °C, respectively. Our results suggest that the incongruent melting of olivine may possibly operate as one of the alternative mechanisms of dissociation reaction driving the phase transformation of olivine in the natural systems.

Plain language summary

The planet Earth was formed from the similar material that constitutes present-day asteroids which is mostly made up of olivine. Therefore, it is important to study olivine at high pressure and high temperature to understand its behavior. Olivine breaks down into bridgmanite and magnesiowüstite in the Earth's lower mantle which is one of the most important reactions that largely controls the physical and chemical properties of the Earth's interior. This breakdown may occur where the olivine remains in the solid-state or may also form by melting of the olivine. The breakdown assemblage of bridgmanite and magnesiowüstite formed by both of these mechanisms and has been reported in few Martian meteorites. Recently, this breakdown assemblage by the solid-state has been reported in the Suizhou meteorite. However, no such assemblage formed by melting has been found in meteorites originated from the asteroid belt. We, for the first time, report the possible

occurrence of bridgmanite and magnesiowüstite formed by incongruent melting of olivine in an ordinary chondrite. This assemblage may have formed at pressure and temperature of ~25 GPa and ~2500 °C. These observations suggest that the dissociation of olivine in the natural systems can also take place by the melting of olivine.

1. Introduction

Olivine is volumetrically the most important phase of the Earth's upper mantle, that undergoes successive pressure-dependent solid-state transformations to wadsleyite (modified spinel structure) at 410-km and then to ringwoodite (spinel structure) at 520-km (Ringwoodite, 1991; Frost, 2008) and ultimately breaks down to form bridgmanite plus magnesiowüstite at 660-km (Ito & Takahashi, 1989). In addition, high-pressure experiments suggest that olivine melts incongruently into magnesiowüstite and liquid at above 8 GPa and 2100 ºC (Presnall & Walter, 1993; Kato et al., 1998; Ohtani et al., 1998) because a compositionally equivalent mixture of magnesiowüstite and liquid has lower free energy than olivine melt at high-pressures (Matsui & Kawamura, 1980; Syono et al., 1981). Therefore, the dissociation mechanism of olivine is pivotal to understand the dynamics of the interior of the Earth and other terrestrial planets because it affects the physical and chemical properties such as densities and elastic velocities of mantle materials.

In addition to occurring in the Earth's interior, high pressure phase transformations, dissociation reactions, and melting textures also occur as shock-induced features that are primarily driven by high pressure and high temperature (HP-HT) conditions produced via high-velocity collisions among asteroid parent bodies and impact events on the Moon and Mars. Most of the high-pressure phases in shocked meteorites occur in and around shock-induced melt veins (SMVs) (e.g., Tomioka & Miyahara, 2017; Miyahara et al., 2020). The solid-state polymorphic transformation of olivine to wadsleyite and ringwoodite have been reported in chondrites (Binns et al., 1969; Ohtani et al., 2004; Xie & Sharp, 2007; Weisberg & Kimura, 2010; Miyahara et al., 2010), Martian meteorites (Greshake et al., 2013; Walton et al., 2014; Miyahara et al., 2016; Takenouchi et al., 2018) and lunar meteorites (Barrat et al., 2005; Zhang et al., 2010). In contrast, olivine grains in contact with the matrix of melt veins and melt pockets of shocked shergottites (DaG 735 and Tissint) have been dissociated to vitrified bridgmanite + ferropericlase (Miyahara et al., 2011, 2016; Walton et al., 2014). Recently, Bindi et al. (2020) reported dissociation of Fe-rich olivine (X_{Fe} = 0.52) to hiroseite (Fe-rich bridgmanite, X_{Fe} = 0.59) and ferropericlase (X_{Fe} = 0.44) by the solid-state transformation in the Suizhou L6 chondrite. However, natural dissociation of olivine by incongruent melting has, to date, not been observed in shocked ordinary chondrites.

The Kamargaon meteorite fell on 13th November, 2015 near the town of Kamargaon, which is located 27 km away from the Golaghat district of Assam, India (Goswami et al., 2016) and was classified as an L6 chondrite (Ray et al., 2017). Previous studies on Kamargaon L6 chondrite described olivine, pyroxene, plagioclase, and metal-sulfide (kamacite, taenite, and troilite) as major rock-forming minerals, whereas chromite as an accessory phase in the chondritic portion (Goswami et al., 2016; Ray et al., 2017). Ray et al. (2017) calculated U-Th-^{4}He, and K-Ar radiometric ages as 170 ± 25 and 684 ± 93 Ma and cosmic ray exposure age as ~7 Ma for Kamargaon L6 chondrite. They observed shock features like presence of mosaicism in olivine and pyroxene grains and maskelynite in the host rock portion, formation of SMVs, polycrystalline troilite and metal-sulfide quenched melt and accordingly suggested that the Kamargaon meteorite has experienced shock stage of up to S5. The mineralogical and textural analysis of SMVs of Kamargaon L6 chondrite has not been studied yet. In the present study, we carefully examined SMV present in the Kamargaon L6 chondrite to understand dissociation and melting textures displayed by olivine grains and their formation mechanisms which further provide clues to estimate the shock conditions in the chondrite parent body.

2. Materials and methods

A small piece (~2g) of Kamargaon chondrite was embedded in a low-viscosity epoxy resin and its surface was polished using diamond paste. Preliminary textural observation and phase identification was done using a scanning electron microscope (SEM) JEOL JSM-6490 installed at Indian Institute of Technology (IIT) Kharagpur, equipped with an energy-dispersive spectrometer (EDS) operating at an acceleration voltage of 15 kV. The fine textural variations and associations of different phases were investigated using a field emission gun scanning electron microscope (FEG-SEM) using a JEOL JSM-7000F at Tohoku University, with an acceleration voltage of 15 kV.

The chemical compositions of the various phases observed in Kamargaon L6 chondrite were obtained by electron probe microanalyser (EPMA) using a Cameca-SX 100 with three wavelength dispersive spectrometers (WDS) operating at an accelerating potential of 15kV at Physical Research Laboratory (PRL), Ahmedabad. To minimize the beam damage and loss of alkali elements, we analysed feldspar grains with the beam current and probe diameter of 10 nA and 5 μm, respectively, whereas all the other phases were analysed with a beam current of 15 nA and minimum beam diameter (~1 μm). Minimum counting times were 20s on the peak and 10s on each side of the background. The following natural silicates, sulfides and metal standards were used for calibration: diopside and plagioclase (Si), rutile (Ti), kyanite (Al), wollastonite (Ca), almandine (Fe in silicates), iron metal (Fe in metal and sulfide phase), olivine (Mg), rhodonite (Mn), jadeite (Na), orthoclase (K), apatite (P), pyrite (S), chromite (Cr), nickel metal (Ni), cobalt metal (Co), vanadium metal (V). The data were corrected for absorption, fluorescence, and atomic number effects using routine PAP (a Phi-Rho-Z correction technique) procedure.

Different mineral phases and their polymorphs were identified using a laser micro-Raman spectrometer, Horiba Jobin-Yvon LabRam HR800 at Indian Institute of Science Education and Research (IISER) Kolkata, India. A microscope was used to focus the excitation laser beam (a He-Ne laser, 633 nm line with 1800 L /mm grating). Laser power on a sample was kept at 7.5 mW and the acquisition times were 10–30 s. For each phase, a Raman shift was acquired in the spectral region of 200–1200 cm^{-1}.

Slice for TEM observations was prepared by a Focused Ion Beam (FIB) system using a JEOL 9320-FIB at Tohoku University. A gallium ion beam was accelerated to 30 kV during the sputtering of the slice, and the slice was approximately 100 nm in thickness. A JEOL JEM-2100F filed-emission (FE)-TEM operating at 200 kV with a JEOL energy-dispersive X-ray spectroscopy (EDS) detector system was used for conventional TEM observation and selected area electron diffraction (SAED) analyses at Tohoku University. We determined the chemical composition of each mineral under the scanning TEM (STEM) mode with the EDS detector. The chemical compositions were corrected using experimentally determined k-factors [albite, pyrope, almandine, San Carlos olivine, and synthetic (Mg,Fe)O].

3. Results

The host rock of the Kamargaon L6 chondrite mainly consists of olivine (Fo_{73-74}), low-calcium pyroxene ($En_{77-80}Fs_{19-22}Wo_{1-2}$), high-calcium pyroxene ($En_{45-46}Fs_{9-10}Wo_{44-46}$), plagioclase ($Ab_{62-70}An_{18-23}Or_{12-15}$), Fe-Ni metal alloy (kamacite and taenite), troilite and a minor amount of phosphate and chromite. The mid-portion of the sample consists of a major thick SMV ranging in width from ~700 to 1600 µm. We observed that numerous olivine grains entrained in the SMV have been dissociated into fine-grained granular assemblage. The extent of dissociation of olivine grains seems to be dependent on the grain size and location of grains in the SMV. The grains which are relatively coarser (>100 µm across) and/or occur near the SMV-host rock boundary (vein edge) are partially dissociated and exhibit heterogeneous texture and composition (Figs. 1a-b). Whereas the grains which are finer (<100 µm across) and/or in the mid-portion of the SMV have been completely dissociated (Fig. 1c). Partially dissociated olivine grains show dissociation texture as well as vesicular texture and the core part of such grains displays vesicular texture. Whereas the outer rim part of the grain exhibits dissociation texture. Spherulitic texture is common in between them (Fig. 1b). The Raman spectra of these dissociated olivine grains exhibit two strong peaks at ~821 (DB1) and ~853 (DB2) cm^{-1} corresponding to characteristic doublet attributed to symmetric and asymmetric stretching vibrations of Si-O bond in SiO_4 tetrahedra in olivine structure (McMillan & Akaogi, 1987) and apparently relatively a weak, less sharp peak at ~664 cm^{-1} indicates the presence of pyroxene glass (Fig. 2) (Kubicki et al., 1992). These measured Raman spectra were used to measure the composition of the residual olivine that escaped the dissociation. The forsterite content of the residual olivine was established using olivine of terrestrial, meteoritic and synthetic origin by combining the doublet (DB1 and DB2) peak positions (Kuebler et al., 2006):

$$\mathrm{Fo} = (80.19x_1 + 399.35x_2 - 0.04x_1^2 - 0.24x_2^2 - 206232.99) \times 100 \qquad (1)$$

where Fo is forsterite content, x_1 and x_2 are peak positions of DB1 and DB2, respectively. Using this relationship, calculated Fo content of the residual olivine in Kamargaon L6 chondrite is ~75 ±10. The Raman spectra of the olivine grains present in the host rock show a strong doublet at peak positions of ~820.4 and ~851.4 cm^{-1} (Fig. 2). Their Fo contents calculated from Eq. (1) of ~75 ±10 and match well with measured Fo content of the host olivine grains of ~74 using electron probe micro analyzer (Table 1). This suggests that the calculated Fo contents of dissociated olivine using Raman data is reliable for our sample.

A thin slice (~20 × 7 × 10 μm) of a bean shaped (~92 × 40 μm) completely dissociated olivine grain in the SMV, adjacent to the vein edge (Fig. 1c) was excavated by a FIB system and analyzed using a TEM to further investigate the assemblage and microtextures of dissociated olivine. A high angle annular dark field (HAADF) image of the TEM slice and STEM EDS analysis exhibit micro porphyritic texture where bright euhedral grains with (Mg,Fe)O composition are embedded in grey matrix consisting of $(Mg,Fe)SiO_3$ (Fig. 3a-b, Table 1). The selected area electron diffraction (SAED) patterns confirm that the bright grains are magnesiowüstite indexed to cubic structure with *a* = 4.38 Å (Fig. 3c) and the grey matrix is orthorhombic enstatite (hereafter orthoenstatite) with *b* = 10.3 Å (Fig. 3d). The magnesiowüstites are dimensionally much larger (up to ~500 nm across) than the elongated orthoenstatites (~50 nm × ~200 nm). The elongated microlites of orthoenstatite grains display dendritic texture (Fig. 3b) which radiates perpendicularly outwards from individual magnesiowüstites. TEM-EDS analyses shows that magnesiowüstite ($Mg_{0.3}Fe_{0.7}O$) have X_{Fe} [molar Fe/(Fe+Mg)] of 0.71 whereas orthoenstatite ($Mg_{1.85}Fe_{0.25}Si_{1.9}O_6$) have X_{Fe} of 0.12 (Table 1).

4. Discussion

Dissociated assemblage of bridgmanite and magnesiowüstite in high-pressure experiments (Frost & Langenhorst, 2002; Sinmyo et al., 2008) and Martian meteorites (DaG 735 and Tissint, Miyahara et al., 2011, 2016) shows equigranular texture with ~120° triple junctions between coexisting bridgmanite and magnesiowüstite grain. These textures have been interpreted to be the evidence of the solid-state transformation due to the simultaneous and random nucleation as well as crystal growth of the coexisting phases. In contrast, a dissociated assemblage of bridgmanite and magnesiowüstite resulting from incongruent melting in high-pressure experiments (Kato et al., 1998; Ohtani et al., 1998) and Martian meteorite (NWA 2737, Miyahara et al., 2019) displays normally euhedral to subhedral grains of the first liquidus phase and finer grained subsequent second liquidus phase that occupy the interstitial space.

Thus, incongruent melting of olivine results in porphyritic texture where the dimensionally larger grains of phenocrysts are generally the first liquidus phase. Dissociated olivines in the Kamargaon L6 chondrite show micro-porphyritic texture with no triple junctions along the grain boundaries. Therefore, we propose that the dissociation assemblage is as a result of the melting of olivine. We carefully examine the texture and Raman spectra of the dissociated part of olivine to test two possibilities for the formation of orthoenstatite: (1) crystallization of orthoenstatite directly from the melt, and (2) crystallization of bridgmanite from the residual melt which was back-transformed to a low-pressure phase of orthoenstatite as a result of subsequent high-temperature event.

To understand the first proposed scenario of crystallization of orthoenstatite directly from the melt we consider the melting experiments in the Mg_2SiO_4-Fe_2SiO_4 system which have shown that the olivine (Fa_{10}) begins to melt incongruently above 8.5 GPa and 2050 °C to magnesiowüstite and Mg-rich silicate liquid (Ohtani et al., 1998). It is likely that with increasing pressure, the incongruent melting temperature of olivine increases but decreases by the addition of fayalite component. We observed that the fayalite content of olivine present in the host rock of Kamargaon is higher (Fa_{26}) than that of the synthetic olivine used by Ohtani et al. (1998). Therefore, we infer that the olivine grains were partially or completely melted incongruently to produce magnesiowüstite and melt, followed by crystallization of orthoenstatite from the residual melt. These orthoenstatites may have crystallized directly from the residual liquid during rapid cooling as indicated by their dendritic texture. The heterogeneity in degree of incongruent melting may possibly be because of the development of temperature gradient in the olivine grains entrained in SMVs as their outer surface is in direct contact with shock melt which makes their inner core portion relatively cooler.

Crystalline structure of natural bridgmanite (X_{Mg} = 0.78) has been reported to coexist with akimotoite in shocked Tenham L6 chondrite (Tschauner et al., 2013). These fine-grained polycrystalline bridgmanite are formed by the solid-state phase transformation from orthoenstatite. Most of the crystalline bridgmanite reported in shocked meteorites are found in vitrified state (Sharp et al., 1997; Tomioka & Fujino, 1997; Tomioka & Kimura, 2003; Chen et al., 2004; Xie et al., 2006) due to the following reasons: (1) bridgmanite becomes unstable at high post-shock temperature after decompression (Durben & Wolf, 1992; Kubicki et al., 1992), (2) it may also get easily damaged by ion sputtering during FIB sample preparation, and (3) under electron beam bombardment in TEM analysis (Sharp et al., 1997; Tomioka & Fujino, 1997). In the present study, no such vitrified phase is observed in the dissociated grains of olivine in Kamargaon. However, orthoenstatite coexisting with magnesiowüstite is identified as a dissociation product of olivine. The Raman spectra from the dissociated portion indicate the presence of pyroxene glass (Fig. 2) although we did not find any vitrified phase with $(Mg,Fe)SiO_3$ composition in the part excavated for TEM observation. Miyahara et al. (2011) observed a similar Raman peak at 665 cm^{-1} from the dissociated olivine in Martian meteorite (DaG 735) and interpreted that it corresponds to vitrified bridgmanite. Thus, the Raman peak at 664 cm^{-1} we observed from the dissociated portion of shocked Kamargaon L6 chondrite might correspond to the remnant of vitrified bridgmanite that was absent in the portion analyzed by TEM. Forsteritic olivine (Fa_{10}) melts incongruently to magnesiowüstite and liquid at 23 GPa but the assemblage changes to magnesiowüstite and bridgmanite at ~25 GPa and ~2500 °C (Ohtani et al., 1998). It is likely that the incongruent melting of olivine took place at or above the pressure of 25 GPa and magnesiowüstite and bridgmanite were crystallized as the dissociation product. In this case, olivine grains may have experienced similar pressure and temperature of ~25 GPa and ~2500 °C, respectively.

We found that albitic feldspar ($Ab_{65}An_{21}Or_{14}$) grains in and around the SMV in Kamargaon L6 chondrite has been transformed into maskelynite. Such transformation requires pressure of ≥ 29-30 GPa (Fritz et al., 2011). This indicates that the pressure was higher than 25 GPa required to produce bridgmanite and magnesiowüstite as the dissociation product. Therefore, we suggest that the crystallization of bridgmanite as the second phase and its subsequent back transformation to orthoenstatite is a more plausible scenario. It has been previously suggested that shock induced melt produced in the SMVs can get superheated far above their liquidus temperature (Sharp et al., 2015). We propose that Mg-rich liquid in the incongruently melted olivine may have been superheated. The bridgmanite started crystallizing from this Mg-rich liquid when the temperature was dropping rapidly but was still above 2500 °C and thus producing a dendritic texture. The bridgmanite may have later back-transformed to a low-pressure phase of orthoenstatite as a result of subsequent high temperature and low-pressure event via a solid-state reaction. Such occurrence of back transformed pyroxene and magnesiowüstite assemblage has been reported as inclusions in sublithospheric diamonds (Hutchison et al., 2001; Zedgenizov et al., 2020). Therefore, orthoenstatite may have retained the morphology of original ultra-fine elongated microlites of bridgmanite. Also, it has been experimentally established that the melting temperature of bridgmanite is lower than that of magnesiowüstite at lower pressures (Zerr & Boehler, 1994). Therefore, alternatively, the subsequent high temperature and lower pressure event may have partially melted the dissociated olivine grains where the bridgmanite occurring in the interstitial space between the magnesiowüstite grains may have melted and crystallized as low-pressure polymorph of orthoenstatite during rapid cooling. The estimated shock pressure of $\geq$ 25 GPa for Kamargaon L6 chondrite is similar to the shock pressure of ~23-26 GPa estimated for other heavily shocked meteorites in which the bridgmanite has formed in the SMVs (Sharp et al., 1997; Tomioka & Fujino, 1997; Tomioka & Kimura, 2003; Chen et al., 2004; Xie et al., 2006; Miyahara et al., 2011).

We calculated the modal proportion of orthoenstatite and magnesiowüstite in the Kamargaon L6 chondrite using the image analysis software (ImageJ) and estimated that the ratio is 69:31 for orthoenstatite and magnesiowüstite which is very similar to the modal proportion of bridgmanite and magnesiowüstite formed by the solid-state transformation in high-pressure experiments and the Martian meteorite of DaG 735 (~70:30) (Ito & Takahashi, 1989; Miyahara et al., 2011). However, extra-terrestrial olivine studied here is slightly Fe-rich (Fa_{26}) compared to olivine (Fa_{8-12}) from the upper mantle. In addition, dissociation mechanism of Kamargaon olivine, i.e., incongruent melting, is different from the solid-state dissociation mechanism of olivine expected in the Earth's mantle. However, natural evidence of dissociation of olivine by incongruent melting to lower mantle assemblage presented in this study and the resulting similar modal ratio of coexisting phases to that of the solid-state dissociation compels us to consider incongruent melting of olivine as possibly one of the alternative mechanisms driving the phase transformation of olivine in the natural systems if provided with the sufficient pressure and temperature.

5. Conclusions

Here we report for the first-time shock-induced incongruent melting of olivine dissociated into magnesiowüstite and orthoenstatite in an ordinary chondrite. Based on the textural observations, we suggest that this dissociated assemblage formed by incongruent melting of olivine into magnesiowüstite and Mg-rich melt in the shocked Kamargaon L6 chondrite.. We propose that the incongruent melting took place at or above the pressure and temperature of ~25 GPa and ~2500 °C to produce magnesiowüstite and Mg-rich melt and subsequently bridgmanite crystallized from the Mg-rich melt. The bridgmanite was heated and back transformed to low pressure phase of orthoenstatite as a result of subsequent high-temperature and low-pressure event. These observations point towards the possibility of incongruent melting operating as an alternate mechanism for phase transformation in the natural systems when subjected to sufficiently high-pressure and high-temperature condition.

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Figures

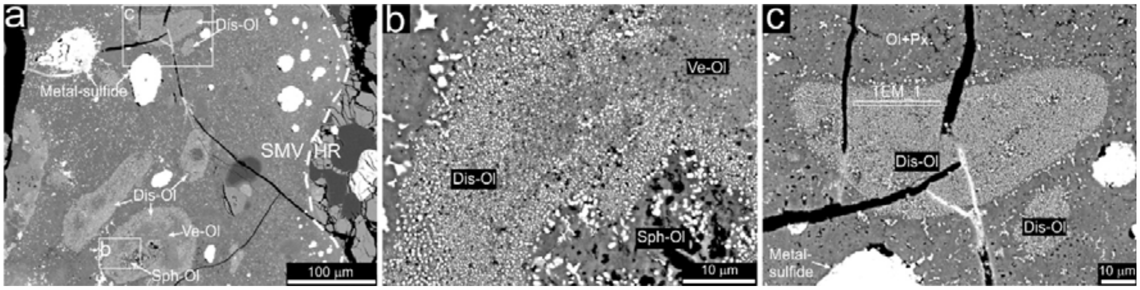

Figure 1 (a) Low magnification back-scattered electron image of the portion of SMV of Kamargaon L6 chondrite shows various completely and partially dissociated olivine grains and metal-sulfide spherules. **(b)** High magnification image of the boxed area in Fig. 1a labelled as b, shows part of the partially dissociated olivine grain. The rim portion of the grains have been dissociated whereas the core portion is vesicular and spherulitic texture. Such heterogeneous texture mainly depicts the formation of temperature gradient in olivine grains entrained in the hot melt vein. **(c)** High magnification image of the boxed area in Fig. 1a labelled as c, shows relatively finer grains which have been completely dissociated. The portions marked as TEM_1 was excavated by using FIB for the TEM analysis. Ve-Ol = vesicular olivine; Dis-Ol = dissociated olivine; Sph-Ol = spherulitic olivine; Ol+Px = olivine + pyroxene assemblage; SMV = shock-melt vein; HR = host rock.

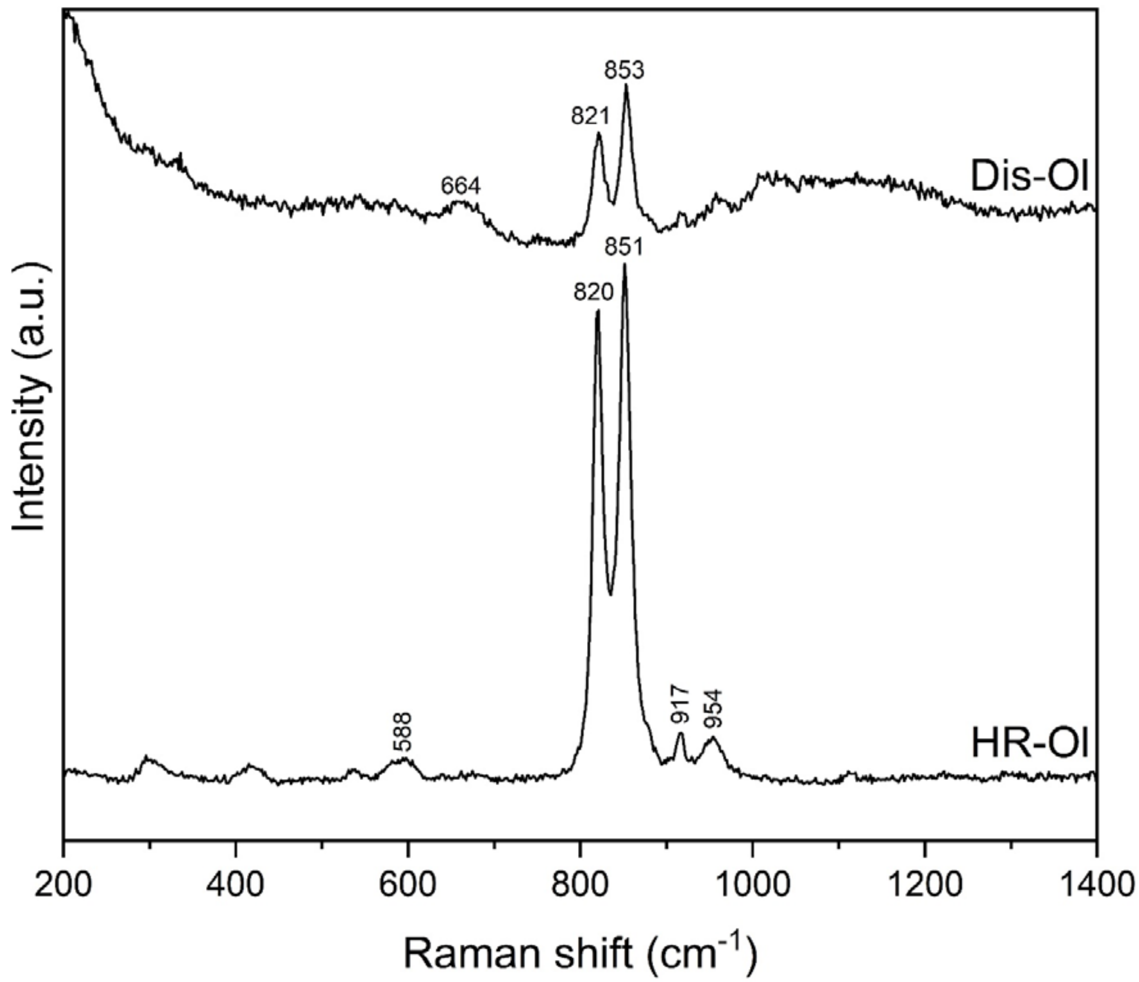

Figure 2 Representative Raman spectra of dissociated (Dis-Ol) and host rock olivine (HR-Ol). Raman analysis of the HR-Ol produces intense doublets at ~820 and ~851 cm^{-1} whereas the Raman spectra of Dis-Ol grains display two strong peaks at ~821 (DB1) and ~853 (DB2) cm^{-1} apparently relatively a weak. Less sharp peak at ~664 cm^{-1} indicates the presence of pyroxene glass.

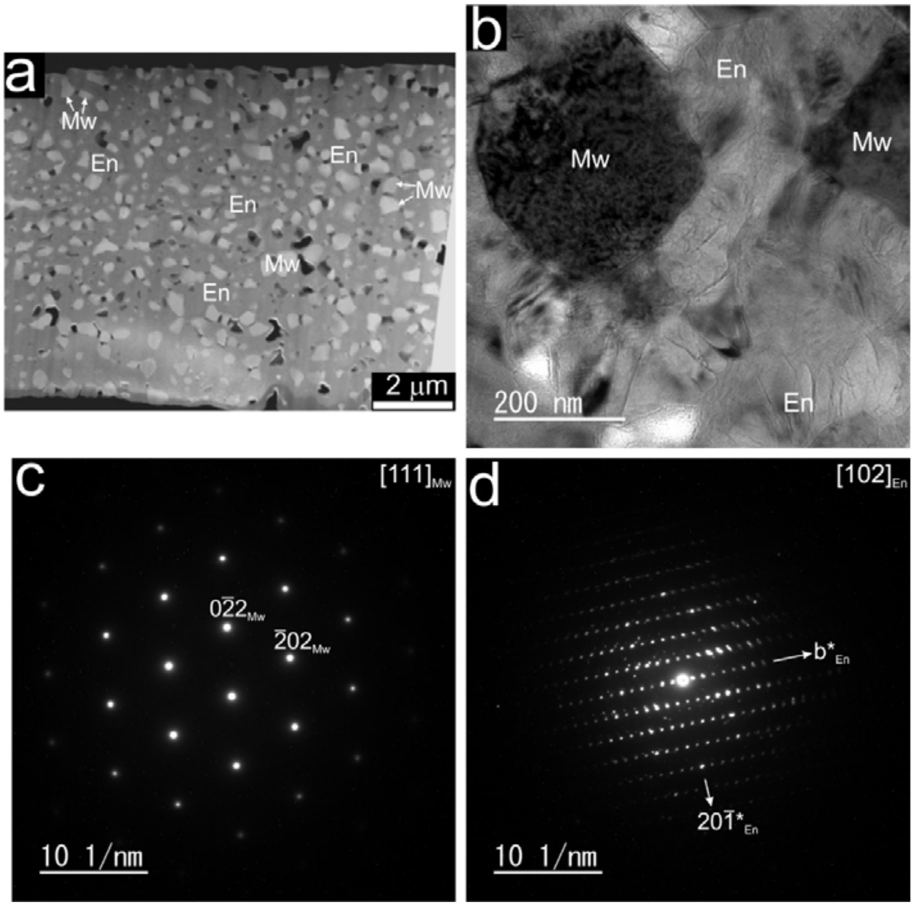

Figure 3 (a) High-angle annular dark field (HAADF) image of the slice cut from the portion marked in Fig. 1c shows micro-porphyritic texture where bright relatively coarser grained magnesiowüstite is set in a grey matrix of finer grained orthoenstatite. **(b)** Bright-field TEM image shows the fine textures of dissociated olivine. Fine elongated microlites of orthoenstatite consist the grey matrix in which the course magnesiowüstite grains are set. **(c)** and **(d)** are electron diffraction patterns of magnesiowüstite and orthoenstatite respectively. Mw = magnesiowüstite; En = orthoenstatite.

Table 1 Chemical composition (in wt. %) of olivine present in the host rock analyzed by EPMA and orthoenstatite and magnesiowüstite formed from dissociated olivine in shock melt vein of the Kamargaon L6 chondrite analyzed by STEM-EDS.

	EPMA		STEM-EDS[#]			
Location	HR-Ol		Dis-Ol			
Phases	Ol	1σ	Oen	1σ	Mw	1σ
n	21		12		7	
SiO_2	37.48	0.47	55.40	1.77	1.55	0.35
FeO*	24.44	0.24	8.51	0.81	80.44	1.09
MnO	0.45	0.04	n.d.	n.d.	n.d.	n.d.
MgO	38.01	0.16	36.09	1.64	18.01	1.19
CaO	0.04	0.03	n.d.	n.d.	n.d.	n.d.
Total	100.42		100		100	
Cation						
Si	0.978	0.009	1.906	0.072	0.016	0.004
Fe^{2+}	0.533	0.006	0.245	0.024	0.280	0.016
Mn	0.010	0.001	-	-	-	-
Mg	1.478	0.007	1.849	0.071	0.703	0.015
Ca	0.001	0.001	-	-	-	-
Oxygen	4		6		1	
Fa	26					
$X_{Fe} \times 100$			12		71	

Fa = fayalite content, X_{Fe} = Fe/(Mg+Fe); Oen = orthoenstatite, Mw = magnesiowüstite; Dis-Ol = dissociated olivine; HR-Ol = host rock olivine; # = Total is normalized to 100 %; * = All iron is assumed to be ferrous, n = number of analyses; 1σ = standard deviation, n.d. = not determined.