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Fractional crystallization of olivine melt inclusion in shock-induced chondritic melt vein

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ABSTRACT

The formation of ringwoodite, wadsleyite and majorite from their parental low-pressure polymorphs in melt veins in chondritic meteorites is usually interpreted to be the result of shock-induced solid-state phase transformation. Formation and survival of individual mineral melt enclaves in the chondritic high-pressure melt was not considered a viable possibility. We report evidence for melting of individual large olivine fragments entrained in melt veins, their survival as melt enclaves in the chondritic melts and their subsequent fractional crystallization at high-pressures and temperatures. The fractionally crystallized olivine melt enclaves appear to be ubiquitous in chondrites. In contrast, Ca-poor pyroxene fragments in the same veins and Ca-poor pyroxene in chondrules entrained do not show any sign of melting. Texture and compositions of olivine fragments are indicative of fractional crystallization from individual olivine melts alone. Fragments of original unzoned olivine ($Fa_{24–26}$) melted, and melts subsequently fractionally crystallized to Mg-rich wadsleyite ($Fa_{6–10}$) and Mg-poor ringwoodite ($Fa_{28–33}$) with a compositional gap of $\leq$26 mol% fayalite. In contrast, compositions of ringwoodite and wadsleyite that emerged from solid-sate phase transformations are identical to that of parental olivine thus erasing any source of enigma. The olivine monomineralic melts barely show any signs of mixing with the chondritic liquid prior to or during their individual fractional crystallization. Our findings demonstrate that the formation of high-pressure minerals during shock events in asteroids also results from melting and fractional crystallization from some individual mineral melts that barely mixed with the chondritic melt host, a mechanism previously not recognized or accepted.

1. Introduction

The high-pressure polymorphs of olivine, wadsleyite and ringwoodite are considered to be the major phases in the Earth's transition zone and probably occur deeper in subducting cold slabs. Many high-pressure and -temperature experiments were conducted in the last two decades in order to uncover the mechanisms of the phase transformations (e.g., Akaogi and Akimoto, 1979; Brearley et al., 1992; Kerschhofer et al., 2000; Mosenfelder et al., 2001). Wadsleyite and ringwoodite were also reported in shock-melt veins of ordinary chondrites (e.g., Putnis and Price, 1979). Phase transformations and textures encountered in shocked chondrites and achieved in high-pressure and -temperature experiments may mimic mechanisms operating in planetary interiors. The formation mechanisms in shock-melt veins of shocked chondrites were also investigated to constrain the magnitude of the equilibrium pressure–temperature conditions and the time scale of the dynamic events (Putnis and Price, 1979; Chen et al., 1996, 2006, 2007; Kimura et al., 2003; Ohtani et al., 2004; Beck et al., 2005; Xie et al., 2006). Previous studies discussed the possibilities of the formation mechanisms of ringwoodite and wadsleyite in shocked meteorites, however some suggested shock durations are unrealistically long (Chen et al., 2004, 2006, 2007). Recently, unique wadsleyite–ringwoodite (Wds–Rgt) assemblages were reported in an olivine porphyritic chondrule in a shock-melt vein of Peace River L6 chondrite (El Goresy et al., 2007; Miyahara et al., 2008a). Surprisingly, the Wds–Rgt crystallites interface displayed a compositional gap of $\leq$32 mol% fayalite, with no evidence for inter-diffusion of Mg and Fe between them. The assemblage was convincingly interpreted to have been formed by fractional crystallization from olivine melts ($Fa_{24–26}$) generated by the shock event.

The transformation mechanisms of high-pressure olivine polymorphs in shocked chondrites were previously interpreted to have resulted from solid–solid state mechanisms, which came mainly

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from the studies of ringwoodite lamella textures in original olivines and polycrystalline ringwoodite (e.g., Chen et al., 1996, 2004, 2006, 2007). The proposed formation mechanism of wadsleyite and ringwoodite by fractional crystallization from olivine melts is quite remarkable, yet it also raises questions that need to be addressed to obtain a satisfactory clarification of details of the different formation processes and their individual conditions. First, is the formation of high-pressure minerals from individual mineral melts an essential mechanism that was overlooked or misinterpreted in the past as solid–solid state transformation (e.g., Lingemann and Stöffler, 1998; Chen et al., 2004, 2006, 2007)? Recognition of the fractional crystallization origin requires unambiguous shifting of the intergrowth textures, evidence for quenched residual melt and individual crystallite compositions that resulted from these different processes. Second, is there any evidence for coexistence of unmixed monomineralic melts also with no interaction with the chondritic liquid of the vein? Indications of reactions between the olivine melt and surrounding minerals in an entrained chondrule or with the Peace River chondritic liquid were not encountered (El Goresy et al., 2007; Miyahara et al., 2008a). We will address these issues in this study because they should open an entirely new venue to estimate the type and magnitude of mineral and silicate melt reactions at high-pressure and -temperature condition not recognized before in chondritic shock-melt veins. We studied shock-melt veins in the L6 chondrites, Allan Hills 78003 (ALHA78003) and Yamato 74445 (Y-74445) to clarify these open queries. A polycrystalline ringwoodite-bearing fragment with Mg-rich wadsleyite-rim was identified in the shock-melt veins of ALHA78003 (Ohtani et al., 2006). Laser micro-Raman spectroscopy indicated that both wadsleyite and ringwoodite coexisted in a similar fragment with a distinct setting enclosed in the shock-melt vein of Y-74445 (Ozawa et al., in press). Here, we encountered two different settings of Wds–Rgt assemblages; one appears to be similar to those reported in Peace River L6 chondrite (El Goresy et al., 2007; Miyahara et al., 2008a). The other different one was encountered for the first time during our investigations. The former was dominant in Y-74445, the later in ALHA78003. We will preferentially focus our interest on the latter novel assemblage and address the other settings for comparative reasons.

2. Materials and methods

Several polished thin sections from ALHA78003 and Y-74445 L6 chondrites were prepared. We encountered many shock-melt veins in these sections. The nature of the minerals under investigation was determined using Laser micro-Raman spectroscopy. We employed a field emission scanning electron microscope, JEOL JSM-71010 for textural observations and assemblage documentation at an accelerating voltage of 15 kV. The chemical compositions were determined using wavelength-dispersive electron microprobe analyzer (EMPA), JEOL JXA-8800M. Analyses were carried out at an accelerating voltage of 15 kV, a beam current of 10–12 nA and a spot size of 5–10 μm. Forsteritic olivine (Si and Mg), rutile (Ti), corundum (Al), fayalite (Fe), Mn-olivine (Mn), Cr_2O_3 (Cr), wollastonite (Ca), jadeite (Na), adularia (K), apatite (P), NiO (Ni) and pyrrhotite (S) were used as standards. However, we could not obtain individual crystallite compositions of both Wds and Rgt because each crystallite size was smaller than the electron beam volume of EMPA. Thus there exists the danger of having average compositions of several neighboring wadsleyite and ringwoodite crystallites with contrasting chemical compositions and encompassed by the electron beam. Several Wds–Rgt assemblages were selected out for transmission electron microscopy (TEM) work. Ultra-thin (120–130 nm) foils of the target areas to be studied by TEM were prepared by a Focused Ion Beam (FIB) system. Detailed FIB procedure is described in Miyahara et al. (2008b). A JEOL JEM-2010 transmission electron microscope operating at 200 kV was employed for conventional TEM and selected area electron diffraction (SAED). We used also a scanning TEM (STEM), JEOL JEM-3000F field emission transmission electron microscope operating at 300 kV with a JEOL energy dispersive X-ray spectroscopy (EDS) detector system. The chemical compositions of individual minerals were obtained by EDS under STEM mode. The compositions were corrected using experimentally determined *k*-factors (San Carlos Olivine and pyrope).

3. Results and discussion

The major mineral constituents of the equilibrated chondrites, ALHA78003 and Y-74445 in the less shocked chondritic host between the shock-melt veins are unzoned olivine (Fa_{24-26}), low-Ca pyroxene (Fs_{21-22}), plagioclase feldspar (Ab_{83-87}), troilite and metallic Fe–Ni. Shock-melt veins in both chondrites contain wadsleyite, ringwoodite, majorite, jadeite and majorite-pyrope$_{ss}$ in diverse settings. Lingunite (Gillet et al., 2000) and tuite (Xie et al., 2002) were also identified in the shock-melt veins of Y-74445. Many troilite and metallic Fe–Ni blebs with eutectic-like intergrowth are also present.

Ubiquitous Wds–Rgt assemblages replaced fragments of original olivine in the shock-melt veins of both chondrites. The Wds–Rgt assemblages can be classified into two types: Type-1 Wds–Rgt assemblage in rare deformed porphyritic chondrules in a shock-melt vein (Fig. 1a and b) and Type-2 isolated Wds–Rgt assemblage in an olivine fragment (Fig. 1c). Although each sample, Y-74445 and ALHA78003 contains both Type-1 and Type-2, Type-1 is dominant in Y-74445, Type-2 in ALHA78003. The original olivine replaced by the Wds–Rgt pair of Type-1 now consists of complex disaggregates (Fig. 1b). EMPA analyses indicate that wadsleyite-dominated portion is slightly enriched in Mg (Fa_{22-26}), whereas the ringwoodite-dominated portion is rich in Fe (Fa_{27-29}). This compositional difference casts doubt of formation by solid-state phase transformation. The original olivine monocrystal fragment of Type-2 was also replaced by both Wds–Rgt pair. The Wds–Rgt assemblage-bearing fragment is now oblong in shape as a result of compression induced flattening and plastic deformation (Fig. 1c). Many olivine fragments are aligned parallel to the walls of the shock-melt vein reflecting the pressure induced by shear stress. The best example of such texture is the chondrule from Peace River shown in Fig. 1a in Miyahara et al. (2008a).

Fragments depicting Type-2 assemblage have a Wds–Rgt aggregate interior surrounded by continuous polycrystalline wadsleyite-rims. The thicknesses of the wadsleyite-rims are <4 μm. EMPA analyses revealed that compositions of wadsleyite-dominated and ringwoodite-dominated parts are Fa_{11-22} and Fa_{27-35}, respectively. The adjacent Ca-poor pyroxene [$(Mg_{3.06}Fe_{0.82}Al_{<0.01}Ca_{0.06})Si_{4.00}O_{12}$] grains show no sign of melting but some converted by solid-state to majorite [$(Mg_{3.08}Fe_{0.86}Al_{0.02}Ca_{0.06})Si_{3.98}O_{12}$] of the same composition.

Type-2 Wds–Rgt assemblage was subsequently investigated by using a surgical FIB-TEM technique (Fig. 1d). We extracted two FIB slices (SP1FIB1 and SP1FIB2) from the assemblage. Both FIB slices also encompass the wadsleyite-rims. These rims consist of polycrystalline idiomorphic wadsleyite crystallites with a knife-sharp boundary to the following layer of wadsleyite + majorite-pyrope$_{ss}$ (Fig. 2a). Only in the rims, wadsleyite crystallites depict preferred orientations (Fig. 2a). SAED patterns show that their long axes appear to be parallel to *b*-axis of wadsleyite. The alignment of the wadsleyite crystallites is suggestive of either habit, lattice preferred orientation or both. Poorly crystallized material with chondritic- or $(Mg,Fe)_2SiO_4$-like compositions wet these crystallites thus evi-