Jadeite in shocked meteorites and its textural variations

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Jadeite occurs as the shocked product of albite feldspar in shocked meteorites, and is one of the most common high-pressure polymorphs in shock-melt veins of meteorites. The characteristic textures of jadeite in shocked ordinary chondrites show that some of jadeite crystals were formed from originally albite feldspar by a solid-state transformation and some were crystallized from a shock-induced albite melt. Based on these textures of jadeite together with the other high-pressure mineral assemblages and their crystallization kinetics, we can estimate the impact conditions such as impact velocity and parent-body size.

Keywords: Jadeite, Ordinary chondrite, Shocked meteorite, Crystallization, Solid-state transformation

INTRODUCTION

Shocked meteorites contain high-pressure polymorphs of constituent minerals, such as high-pressure polymorphs of olivine, pyroxene, feldspar, and silica minerals. Such high-pressure polymorphs were formed by collisions in the early solar system and the impact events on the surfaces of Mars and Moon. Recent discoveries of new high-pressure polymorphs (e.g., El Goresy et al., 2000; Hollister et al., 2014; Bindi et al., 2017; Litasov and Podgornykh, 2017) drastically increased the number of meteorite types containing high-pressure polymorphs since early 2000s. Figure 1 shows the classification tree of meteorites. The meteorite groups containing high-pressure polymorphs are shown as the shaded boxes in this figure. Now we can see 13 groups of meteorites contain high-pressure polymorphs.

Albite is one of the major constituents of ordinary chondrites. Some albite grains become maskelynite in shocked ordinary chondrites. Albite grains entrained in or adjacent to the shock-melt veins of these meteorites experienced both high-pressure and high-temperature conditions due to localized frictional heating during the shock events. Accordingly, albite entrained in or adjacent to the shock-melt veins transformed into its high-pressure polymorph. The phase diagram of albite based on the static high-pressure and high-temperature experiments indicates that albite transforms to NaAlSi3O8 with hollandite-structure (lingunite) or CaFe2O4-type NaAlSiO4 + stishovite subsequent to jadeite + SiO2 assemblages with increasing pressure and temperature (e.g., Holland, 1980; Yagi et al., 1994; Liu, 2006; Tutti, 2007). Jadeite occurs as the shocked product of albite feldspar, and is one of the most common high-pressure polymorphs in shocked meteorites. Jadeite and tissintite, Ca-bearing isostructural phase of jadeite, have been discovered in six different types of meteorites with compositions close to basalt. Jadeite was reported in H, L, and LL ordinary chondrites (e.g., Ohtani et al., 2004; Miyahara et al., 2013; Ozawa et al., 2014) and CB group carbonaceous chondrite (Miyahara et al., 2015). Whereas, shergottite and eucrite contain tissintite which is the isostructural phase of jadeite containing Ca in its structure (Ma et al., 2015; Pang et al., 2016). Identification of jadeite in meteorites has been made by using micro-Raman spectroscopy. The typical Raman spectrum of jadeite in the shock melt vein of Chelyabinsk LL5 ordinary chondrite measured with a micro-Raman spectrometer (JASCO NRS-5100) is shown in Figure 2.

Two distinct textures, i.e., the solid state transformation and crystallization from the melt, have been observed as the high pressure polymorphs of minerals including jadeite, olivine, low-Ca pyroxene, and garnet.
The contrasting textures are observed in olivine in different L6 chondrites (Ohtani et al., 2004, 2006). Olivine crystals existing along the shock–melt veins in Yamato (Y)–791384 L6 chondrite contain ringwoodite with a lamellar texture. The lamellar texture indicates that ringwoodite was formed by the solid–state transformation with a mechanism of the coherent nucleation and succeeding incoherent nucleation (Ohtani et al., 2004; Miyahara et al., 2010). On the other hand, wadsleyite–ringwoodite assemblage occurred in the shock–melt veins of Allan Hills (ALH) 78003 and Peace River L6 ordinary chondrites, indicating overgrowth in the melt at high pressure (Ohtani et al., 2006) or fractional crystallization from the melt (Miyahara et al., 2008, 2009).

As mentioned above, jadeite is commonly identified in many kinds of shocked meteorites as a high-pressure polymorph formed from albite feldspar. The occurrence of jadeite in shocked meteorites has been investigated in detail by using laser micro–Raman spectroscopy, scanning electron microscopy (SEM), transmission electron microscopy (TEM) and X-ray diffraction (XRD). Different textures of formation of jadeite with or without silica and lingunite from albite feldspar has been reported in many previous studies. These phase assemblages record the pressure and temperature conditions during the shock event occurred on its parent body. Here, we review the recent works on textures of jadeite in several shocked meteorites, and discuss the pressure and temperature conditions during the shock events for formation of jadeite with different textures.

**TEXTURAL VARIATIONS OF JADEITE IN SHOCKED METEORITES**

**Solid-state transformation**

Kimura et al. (2000) confirmed the existence of jadeite in albite feldspar grains entrained in or adjacent to the shock-
melt veins of Yamato (Y)-75100 H6 ordinary chondrite using a laser micro-Raman spectroscopy for the first time. When jadeite is formed by the decomposition reaction of albite, silica phase should be accompanied with jadeite based on the composition of albite; i.e., albite (NaAlSi₃O₈) → jadeite (NaAlSi₂O₆) + silica (SiO₂) (e.g., Birch and LeCompte, 1960; Boyd and England, 1963). Y-75100 also contains wadsleyite, lingunite and majorite and LeCompte, 1960; Boyd and England, 1963). Y–O₈ melt veins of Yamato (Y)

**Figure 2.** A typical Raman spectrum of jadeite from Chelyabinsk LL5 ordinary chondrite (Ozawa et al., 2014) measured with a micro-Raman spectrometer (JASCO NRS-5100). Ol, Raman peaks of neighboring olivine.

melt veins of Y-74445 L6 ordinary chondrite (Ozawa et al., 2009). Original albite feldspar (Ab₈₃-₈₅An₁₀Or₅-₇) grains entrained in the shock-melt veins of Y-74445 transformed into jadeite and lingunite without any crystalline silica phases. The lamellar intergrowth of jadeite and lingunite indicates these phases were formed by the solid state transformation. Jadeite crystallite assemblages contain many ‘particle–like’ materials as shown in Figure 3B. Ozawa et al. (2009) described that the ‘particle–like’ material was silica-rich amorphous material, and proposed that original albite feldspar transformed to jadeite and the amorphous material. Similar jadeite crystallite assemblages were also observed in the albite feldspar (Ab₈₃-₈₅An₁₀Or₅-₇) grains entrained in the shock-melt veins of Sahara 98222 L6 ordinary chondrite (Ozawa et al., 2009). Numerous particle–like or stinger-like materials occurred coexisting with jadeite in the albite feldspar grains of Sahara 98222. Their typical textures are shown in Figure 4. Ozawa et al. (2009) suggested that the particle–like and stringer-like materials may be composed of silica-rich amorphous materials. Further detail investigation on jadeite in shocked ordinary chondrites was conducted using focused ion beam (FIB)-assisted TEM and Raman spectroscopy. Miyahara et al. (2013) investigated jadeite occurring in the albite feldspar (Ab₉₄-₈₆An₉₋₁₀Or₅-₇ in Y-791384; Ab₈₀-₈₁An₁₃-₁₄Orₛ-₆ in Y-75100) grains entrained in or adjacent to the shock-melt veins of Y-791384 L6 and Y-75100 H6 ordinary chondrites. Synchrotron XRD patterns and TEM observations revealed that the albite feldspar grains contain jadeite and residual amorphous (or poorly-crystallized) materials.

Kubo et al. (2010) conducted in situ X-ray diffraction measurements of two kinds of feldspar (albite and labradorite) under the conditions of high-pressure and high-temperature below the liquidus temperature of the system. They observed that the amorphization pressure of feldspar decreases with increasing temperature. They also observed that jadeite forms first from amorphous feldspar, whereas the nucleation of other minerals such as stishovite or garnet is significantly delayed.

Based on the TEM observations of albite feldspar grains including jadeite both in the synthetic samples and ordinary chondrites, Miyahara et al. (2013) proposed following jadeite formation mechanism; i.e., original albite becomes amorphous at high pressure, and subsequently jadeite is crystalized within the amorphous albite domains with increasing pressure and temperature. They also suggested that the dissociation reaction proceeded under the solid-state conditions because the pseudomorph textures of poly-crystalline albite (now amorphous) were remained. When albite transforms into jade-
ite + silica, long distance atomic diffusion is essential. Thus the albite dissociation reaction is time-dependent and controlled by the grain-boundary diffusion (Kubo et al., 2010; Miyahara et al., 2013). The approximate duration of high-pressure and high-temperature conditions induced by the shock event occurred in a parent-body of ordinary chondrite was estimated to be from several milliseconds to several seconds (Ohtani et al., 2004; Beck et al., 2005; Xie et al., 2006; Miyahara et al., 2010). Thus, occurrence of jadeite which does not coexist with stishovite can be explained as a result of the crystallization kinetics, i.e., stishovite can hardly be formed in shocked ordinary chondrites due to the limited duration of high-pressure and high-temperature conditions and critical differences in nucleation rate between jadeite and stishovite as was shown experimentally by Kubo et al. (2010).

Northwest Africa 8275 (hereafter, NWA 8275), which is classified into LL7 includes pervasive shock-melt veins, suggestive of a heavy shock event occurred on LL ordinary chondrite parent-body. Several feldspar grains are entrained in the shock-melt veins of NWA 8275. The BSE images of the textures of this meteorite are shown in Figures 5A and 5B. Some feldspar grains entrained in the shock-melt veins dissociate into jadeite + coesite completely in this meteorite which indicates higher shock induced temperature or longer duration of the shock event compared to many other shocked meteorites in which coesite/stishovite did not appear due to their sluggish kinetics. A typical texture of jadeite + coesite assemblage replacing original albite feldspar in NWA 8275 LL7 is shown in Figure 5A. On the other hand, Figure 5B indicates the jadeite crystallites with dendritic

Figure 3. BSE images. (A) lamellar textures composed of jadeite and lingunite observed in the shock-melt vein of Y-74445 L6. Original feldspar grains transformed to the jadeite and lingunite lamellar intergrowth. (B) A high-magnification image of the white rectangular area in (A). Jadeite contains the particle-like amorphous silica-rich material (Pcl). Jd, jadeite; Lg, lingunite (hollandite).

Figure 4. BSE images. (A) particle-like silica-rich amorphous materials (Pcl) coexisting with jadeite formed in the albite grains of Sahara 98222 L6 (Ozawa et al., 2009). (B) stringer-like amorphous materials (Stg) in the same chondrite. Pcl, particle-like amorphous materials; Stg, stringer-like amorphous materials; Jd, jadeite; Ol, olivine; Rw, ringwoodite; Fe-Ni, metallic Fe-Ni.
textures observed in the same meteorite. The dendritic textures of jadeite crystallites indicate crystallization of jadeite from the feldspar melt, which is explained in detail in the next section.

Crystallization from feldspar melt

Another different transformation mechanism observed in shocked ordinary chondrites is the crystallization of jadeite from shock-induced feldspar melt. We can observe two different textures suggesting the crystallization of jadeite from the shock-induced feldspar melt; 1) jadeite crystallites with dendritic textures showing rapid nucleation and crystallization from the feldspar melt, 2) spherulite-like jadeite suggesting nucleation and growth from the interface of surrounding minerals. A typical example of jadeite crystallite with a dendritic texture was observed in the albite feldspar (Ab$_{84}$An$_{11}$Or$_{5}$) grains entrained in the shock-melt veins of Chelyabinsk LL5 ordinary chondrite (Ozawa et al., 2014). Typical dendritic jadeite crystallites are shown in Figure 6. Many dendritic jadeite crystallites are distributing in feldspar glass. Individual jadeite crystallites in the feldspar glass do not show specific crystallographic orientations. Residual glassy (amorphous) material (Gl in Fig. 6B) occupies the interstices of the jadeite crystallites. These features suggest nucleation and rapid grain-growth from the albite feldspar melt. Typical jadeite crystallites were observed in the shock-melt veins of Novosibirsk H5/6 ordinary chondrite (Fig. 7). Many jadeite crystallites were observed in the feldspar glass, and the assemblage appears to have a spherulite-like texture. The jadeite crystallite assemblages with a spherulite-like texture always coexist with glass (amorphous material, Gl in Fig. 7). The spherulite-like texture occurred preferentially along the surface of surrounding crystals such as low-Ca pyroxene, olivine and troilite, indicating heterogeneous nucleation and rapid grain growth from the albite feldspar melt (Bazhan et al., 2017). Jadeite crystallites with a dendritic texture and a spherulitic texture do not accompany any silica phases.

FORMATION CONDITIONS OF JADEITE IN METEORITES

Figure 8 shows the phase diagram of albite at high-pressure and high-temperature and the kinetic boundaries for nucleation of jadeite and stishovite [Bell and Roseboom (1969), Ozawa et al. (2014), and Kubo et al. (2010) were modified]. Albite transforms through a mixture of jadeite and coesite/stishovite to lingunite with increasing pressure. Based on this phase diagram, jadeite possesses a wide stability field from 3 to 20 GPa. Melting temperatures of albite and a mixture of jadeite and coesite are significantly lower than the melting temperature of host-rocks (Fig. 8), indicating albite can be molten during a shock event remaining surrounding olivine and pyroxenes in solid-state. In shocked ordinary chondrites, original albite feldspar in the host-rocks transformed to several different phases such as maskelynite, jadeite + silica-rich amorphous material, jadeite + coesite, jadeite + melt (glass) and lingunite depending on the pressure and temperature conditions. Based on the phase relations shown in Figure 8, we can estimate the pressure and temperature conditions recorded in shocked ordinary chondrites during the shock events by taking into account of coexisting high-pressure polymorphs.

Coexistence of jadeite and amorphous silica is observed in several shocked ordinary chondrites (Ozawa et al., 2009). According to Kubo et al. (2010), amorphous silica crystallizes as stishovite or coesite only at high-
temperature; i.e., existence of coesite with jadeite in NWA 8275 LL7 ordinary chondrite (Fig. 5A) indicates crystallization at high-temperatures near the solidus. Dendritic jadeite crystallites showing crystallization from the melt observed in different parts of the same meteorite (Fig. 5B) also indicates evidence for formation at high-temperatures around the solidus. The sluggish kinetics in nucleation of stishovite compared to jadeite is clearly observed by the high-pressure and high-temperature in-situ X-ray diffraction experiments (Kubo et al., 2010); 10% crystallization temperature of jadeite in one second locates at around 1000–1400 °C with a positive pressure dependency, whereas that for stishovite locates at temperatures above 2000 °C (Fig. 8). The solidus and liquidus temperatures of albite and jadeite + coesite assemblage locate around 1400–1800 °C, which would indicate the nucleation of coesite is rather fast at temperatures near the solidus. In NWA 8275 LL7, Chelyabinsk LL5, and Novosibirsk H5/6 ordinary chondrites, jadeite shows evidence for crystallization from the melt. These ordinary chondrites do not contain high-pressure polymorphs showing pressure conditions above ~15 GPa (Ozawa et al., 2014; Miyahara et al., 2016; Bazhan et al., 2017). The pressure range recorded in these ordinary chondrites suggests impact velocity ~0.4–1.5 km/s following Rankine–Hugoniot’s relations (Ozawa et al., 2014). Their parent-body sizes were estimated to be around 0.15–0.19 km based on shock wave duration deduced from the cooling rate of the shock melt veins (e.g., Ozawa et al., 2014). Considering existence of jadeite from the melt and/or jadeite + coesite assemblage in these chondrites, the pressure–temperature path during the impact event is depicted in Figure 8. On the other hand, many L-type chondrites and some H-type chondrites (Sahara 98222 L6, Y-74445

Figure 6. BSE images. (A) Typical jadeite crystallites with dendritic textures nucleated in the melt spot observed in Cheryabinsk LL6 chondrite. (B) High-magnification image of the white rectangular area in (A). Jd, jadeite; Gl, glass; Ol, olivine; Pyx, low-Ca pyroxene.

Figure 7. BSE images. (A) Typical jadeite crystallites with a spherulite-like texture observed in Novosibirsk H5/6. (B) A high-magnification image of the white rectangular area in (A). Jd, jadeite; Gl, glass; Pyx, low-Ca pyroxene; Ol, olivine; Tro, troilite. (Photos courtesy by I. Bazhan)
L6, Y–791384 L6, and Y–75100 H6) show clear evidence for the solid-state transformation of jadeite. These ordinary chondrites include other high-pressure polymorphs such as ringwoodite, wadsleyite, majorite and akimotoite together with jadeite (Ohtani et al., 2004; Ozawa et al., 2009; Miyahara et al., 2010; Fudge et al. 2015). The parent-body sizes of these chondrites estimated by the transformation kinetics are also small (~ 10 km) although the impact velocity (~ 2.0 km/s) (Ohtani et al., 2004) is larger than that recorded in LL- and H-type chondrites described above. The expected pressure-temperature path of the chondrites is also shown in Figure 8. It is clear that the former (NWA 8275 LL7, Chelyabinsk LL5, and Novosibirsk H5/6) and the later (Sahara 98222 L6, Y–74445 L6, Y–791384 L6, and Y–75100 H6) parent-bodies experienced different pressure-temperature paths each other, indicating different type impact events.

An onion-shell model with a diameter of ~ 50–100 km has been presented for the parent-body of H-type ordinary chondrite (e.g., Kleine et al., 2008). Whereas the rapid cooling of H-type chondrites deduced by the speed meter based on compositional variation of the coexisting minerals (e.g., Ganguly et al., 2013) suggested smaller parent-body for these meteorites, and also suggested multistage fragmentation and reaccretion of the fragmented bodies in the early solar system. The parent-body sizes deduced from the kinetics of high-pressure polymorphs are considerably smaller than the expected parent-body size. The evidence for multiple collision and small size of their parent bodies recorded in these meteorites is consistent with the rubble pile model of asteroids (e.g., Fujiwara et al., 2006). The high-pressure polymorphs formed in the shocked ordinary chondrites might have recorded the history of some stages of multiple collision of the fragments after major disruption of original parent-body.

CONCLUSIONS

Jadeite (or Tissintite) is observed in shocked meteorites, such as L, LL, and H chondrites, CB chondrite, shergottite, and eucrite. Under the high-pressure and high-tem-
perature conditions of shock events, albite feldspar transformed into maskelynite, jadeite (or tissinite) with or without silica, and lингунite. Jadeite is stable in the pressure range from 3 to 20 GPa based on the phase diagram of albite. The characteristic textures show that some of jadeite crystals were formed by a solid–state transformation and some were formed by crystallization from the melt. Two distinct pressure–temperature paths are estimated based on the textures of jadeite and other high–pressure assemblages, i.e., one path experienced a slow speed collision (~ 0.4–1.5 km/sec) and high–temperature near or above the melting temperature of albite or jadeite + coesite/stishovite, whereas another experienced relatively higher speed collisions (> 2 km/sec) below the solidus of basaltic host–rocks. The parent–body sizes of these chondrites estimated by the crystallization kinetics of high–pressure polymorphs are smaller than those estimated as the primary parent–bodies of chondrites based on their cooling history, suggesting that the high–pressure polymorphs recorded the history of multiple collision of fragments after major disruption of the parent–body of ordinary chondrites.

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