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Letters

Jadeite formation in shocked ordinary chondrites

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ABSTRACT

Albitic feldspar in shocked ordinary chondrites (Yamato 791384 L6 and Yamato 75100 H6) and albite recovered from static high-pressure and high-temperature synthetic experiments (Kubo et al., 2010) were investigated with a transmission electron microscope (TEM) subsequent to a conventional micro-Raman spectroscopy analysis to clarify albite dissociation reaction under high-pressure and high-temperature condition. When jadeite forms from albite, SiO₂ phase as a residual phase of albite dissociation reaction should accompany jadeite from the stoichiometry. However, albitic feldspar in and adjacent to shock-melt veins of the shocked chondrites dissociates into jadeite+residual amorphous (or poorly-crystallized) material having varied chemical compositions between jadeite and SiO₂ phase. TEM observations of albitic feldspar in the shocked chondrites and albite recovered from the static high-pressure and high-temperature synthetic experiments show that jadeite crystallization is initiated by grain refinement of albite (or albitic feldspar). Nucleation occurs along grain-boundaries or at triple-junctions of the fine-grained albite crystal assemblage. Jadeite crystal starts to grow from the nucleus through grain-boundary diffusion. Considering pressure condition recorded in the shock-melt veins of the shocked chondrites, stishovite is the most likely as a residual SiO₂ phase accompanying jadeite. High-pressure and high-temperature condition induced by a dynamic event is very short. Stishovite would be hardly formed through a dynamic event due to sluggish nucleation rate of stishovite compared with that of jadeite, thus leading to induce heterogeneous and incomplete albite dissociation reaction; albite dissociates into jadeite+residual amorphous material.

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1. Introduction

High-pressure and high-temperature conditions induced by a planetesimal collision are recorded in many shocked chondrites (Chen et al., 1996; Sharp et al., 1997; Tomioka and Kimura, 2003; Ohtani et al., 2004; Walton et al., 2006; Zhang et al., 2006; Miyahara et al., 2008a, 2011a; Ozawa et al., 2009; Feng et al., 2011). Albite is one of major constituent minerals of an ordinary chondrite. Albite contained in shocked ordinary chondrites can be transformed to a high-pressure polymorph or amorphous material (maskelynite). Static high-pressure and high-temperature synthetic experiments indicate that albite transforms to NaAlSi₃O₈ with hollandite-structure (lingunite) or CaFe₂O₄-type NaAlSiO₄+stishovite subsequent to jadeite+SiO₂ phase with increasing pressure and temperature conditions (Liu, 1978, 2006; Holland, 1980; Yagi et al., 1994; Gillet et al., 2000; Tutti, 2007).

Terrestrial jadeite occurs in orogenic belts, and is formed by high-pressure and low- to medium-temperature subduction-related metamorphism (e.g., Harlow and Sorensen, 2004). Although most of the terrestrial jadeite originate from albite dissociation reaction as deduced from static high-pressure and high-temperature synthetic experiments, its formation mechanism is still under debate (e.g., Miyajima et al., 2001; Morishita et al., 2007).

Kimura et al. (2000) reported the existence of jadeite from shocked ordinary chondrites first using a laser micro-Raman spectroscopy. Localized areas in shocked ordinary chondrites can be heated beyond the melting temperature by friction along a fracture and/or the concentration of stress in addition to high-pressure condition prevailing during a dynamic event, thus leading to formation of a shock-melt vein and/or melt pocket. Raman analysis indicates that jadeite exists in albitic-composition grains entrained in, or adjacent to, a shock-melt vein. However, the presence of jadeite has been deduced only from a Raman spectrum. In addition, the formation mechanism of jadeite in shocked ordinary chondrites is enigmatic. When jadeite forms through albite dissociation reaction, an SiO₂

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phase should accompany it based on stoichiometry and static high-pressure and high-temperature synthetic experiments (Liu, 1978; Holland, 1980). However, in the shocked ordinary chondrites, an SiO₂ phase accompanying jadeite has not been detected by Raman spectroscopy analysis. It is likely that albitic feldspar in the shocked ordinary chondrites transforms to jadeite while maintaining its original chemical composition, which is very inapprehensible. Similar occurrences have been reported from many shocked H, L, LL-ordinary chondrites, and also from Ries crater (James, 1969; Ohtani et al., 2004; Miyahara et al., 2008a, 2009, 2010, 2011b; Ozawa et al., 2009).

Accordingly, we have investigated albitic feldspars in Yamato 791384 L6 (hereafter, Y-791384) and Yamato 75100 H6 (hereafter, Y-75100) ordinary chondrites by transmission electron microscopy (TEM) subsequent to conventional micro-laser-Raman spectroscopy analysis and scanning electron microscopy (SEM) to clarify the nature, occurrence and formation mechanism of jadeite. Kubo et al. (2010) conducted static high-pressure and high-temperature synthetic experiments using albite as a starting material to clarify its phase transformation mechanism and kinetics. We have also investigated several samples recovered from the synthetic experiments via SEM and TEM to compare with the jadeite in the shocked ordinary chondrites.

2. Experimental methods

2.1. Shocked ordinary chondrites

Petrographic thin sections were prepared from the Y-791384 and Y-75100 chondrite chip samples, including several shock-melt veins. We observed textures and minerals in the thin sections with an optical microscope. Mineralogy was determined using a laser micro-Raman: a JASCO NRS-2000 spectrometer with a liquid nitrogen-cooled CCD detector. A microscope was used to focus the excitation laser beam (the 487.99 nm lines of a Princeton Instruments Ar⁺ laser). To check the mineral phases, individual Raman measurements were performed. Acquisition times were 30–120 s. The laser power on the sample was kept at 8–12 mW

to reduce damage. For each phase, two spectra were acquired in the spectral region of 200–1300 cm⁻¹ and then averaged. We employed a field-emission gun scanning electron microscope (FEG-SEM): JEOL JSM-71010 for textural observations at an accelerating voltage of 15 kV in addition to a conventional SEM: JEOL JSM-5410 operating at 15 kV. The chemical compositions were determined using a wavelength-dispersive electron micro-probe analyzer (EMPA): JEOL JXA-8800M and JEOL JXA-733. Analyses were carried out using an accelerating voltage of 15 kV, a beam current of 4–10 nA and a defocused spot size of 5–10 μm (to reduce beam damage and loss of alkali elements). Forsterite (Si and Mg), rutile (Ti), corundum (Al), fayalite (Fe), Mn-olivine (Mn), Cr₂O₃ (Cr), wollastonite (Ca), jadeite (Na), adularia (K), NiO (Ni) and pyrrhotite (S) were used as standards. Quantitative analysis was corrected by the ZAF procedure.

A part of the sample was excavated with a Focused Ion Beam (FIB) system: JEOL JEM-9320FIB, and the extracted slice was placed on a culet of single diamond. The excavated samples on the diamond were scanned at the BL10XU beam line (SPRING-8). A monochromatic incident X-ray beam with a wavelength of 0.4149 (1) Å was collimated to a diameter of less than 10 μm. X-ray diffraction spectra were collected on an imaging plate (IP) using an exposure time of 5 min. The X-ray diffraction spectrum of cerium dioxide (CeO₂) was used to determine the wavelength and the distance between the sample and the IP.

A slice of the target area to be studied by a transmission electron microscope (TEM) was prepared by a JEOL JEM-9320FIB and a dedicated optical microscope with a manipulator. A gallium ion beam was accelerated to 30 kV during the sputtering of the slice by the FIB. Details of the procedure were described in Miyahara et al. (2008b). Resultant slices were 100–130 nm in thickness. A JEOL JEM-2010 transmission electron microscope operating at 200 kV was employed for conventional TEM and selected area electron diffraction (SAED). We also used 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 chemical compositions were corrected using

Table 1
EMPA analyses.

Oxides	Y-791384				Y-75100			
	Ab-Jd	σ	Mask*	σ	Ab-Jd	σ	Mask	σ
SiO ₂	67.15	0.97	67.19	0.84	66.03	0.81	66.29	0.65
Al ₂ O ₃	21.59	0.32	21.43	0.46	21.66	0.39	21.71	0.19
FeO	0.86	0.33	0.83	0.29	1.14	0.55	0.62	0.27
CaO	1.89	0.07	1.92	0.10	2.87	0.10	2.83	0.12
Na ₂ O	9.51	0.15	9.52	0.13	9.25	0.57	9.24	0.17
K ₂ O	0.94	0.14	0.96	0.13	1.04	0.32	0.96	0.06
Total (wt%)	101.94		101.86		101.99	1.19	101.64	
O = 32								
Si	11.613	0.018	11.630	0.041	11.483	0.070	11.524	0.027
Al	4.401	0.028	4.372	0.068	4.439	0.062	4.448	0.028
Fe(ii)	0.124	0.048	0.121	0.042	0.166	0.079	0.089	0.040
Ca	0.350	0.011	0.356	0.017	0.534	0.019	0.528	0.023
Na	3.189	0.044	3.195	0.041	3.118	0.196	3.114	0.056
K	0.208	0.032	0.213	0.030	0.231	0.069	0.213	0.012
Total	19.885		19.888		19.972		19.915	
Ab	85		85		80		81	
An	9		9		14		14	
Or	6		6		6		6	
n =	4		5		11		4	

Ab-Jd=albitic-composition grain including jadeite (+residual amorphous material). Mask=maskelynite. n=number of analysis.

* Miyahara et al. (2011b).

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