Shock metamorphism and Ar-Ar ages of ordinary chondrites

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Introduction

Generally, shock metamorphism in meteorites reflects shock conditions of a collisional event(s), such as shock pressure and temperature, and frequency. One of the essential factors controlling shock pressure is an impact velocity, which is strongly related to planetary orbital movements (e.g., orbital radii and eccentricities). Therefore, revealing shock conditions from meteorites will help to constrain asteroids' moving. Combining it with Ar-Ar chronology as a shock age, we expect to reveal a history of asteroids' orbital change in the solar system. Therefore, we are now proceeding analyses of both shock metamorphic textures and Ar-Ar ages of meteorites to reveal a time transition of shock metamorphism and a frequency of shock events. In this study, we focus on ordinary chondrites and report their shock-metamorphic features and shock ages.

Sample and Methods

We prepared chips of five H chondrites and one L chondrite supplied from the University Museum, the University of Tokyo. Three out of five H chondrites are H4 (Wellman (c), Salaices, and Ochansk), and two are H5 (Nuevo Mercurio) and H6 (Ozona). The last one is L6/7 chondrite Seagraves (c) (at first, we have thought that we prepared H4 chondrite "Seagraves," but its label and our observation confirms that this is L6/7 "Seagraves (c)" distinct from H4 "Seagraves"). Although H chondrites tend to show weaker shock metamorphism than L chondrites, H chondrites yield a wide range of Ar-Ar ages, such as <1.5 Ga and 3.5-4.5 Ga. Thus, H chondrites are suitable for comparing degrees of shock metamorphism throughout the solar system history. We made thin sections for microscope observation and specimens for Ar-Ar chronological analysis (21.0-26.3 mg) from the same chips of each meteorite to ensure a correlation between shock metamorphic textures and shock ages. Mineralogical and petrological observations were performed at NIPR using optical microscopy and field-emission scanning electron microscopy (FE-SEM, JEOL JSM-7100F). Electron back-scattered diffraction (EBSD, Oxford Instruments, AZtec) analyses were conducted for mineral phase identification. The specimens for Ar-Ar analysis are irradiated with neutrons at Institute for Integrated Radiation and Nuclear Science, Kyoto University. The Hb3gr hornblende and synthesized CaF_2 and K_2SO_4 are also irradiated to monitor neutron flux and correct neutron-produced Ar interferences, respectively (Roddick 1983). Each specimen is heated step-by-step in about 15 steps from 500 to 1800 ºC. After gas purification, isotope compositions of the extracted Ar are analyzed by modified-VG3600 noble gas mass spectrometer at the University of Tokyo (Ebisawa et al. 2004).

Results

Our observation revealed that Nuevo Mercurio (H5) and Ozona (H6) have almost no shock metamorphic features because all minerals show sharp extinction under crossed nicols, although healed cracks and Fe-sulfide trails are commonly observed. The Ar-Ar ages of Nuevo Mercurio and Ozona are 4.524±0.004 Ga and 4.488±0.007 Ga, respectively. The high-porosity in Nuevo Mercurio also supports that this meteorite records no shock metamorphism. On the other hand, three H4 chondrites, Wellman (c), Salaices, and Ochansk, include shock metamorphic features. Olivine and pyroxene in these meteorites show wavy extinction. There are thin shock veins in each meteorite, and albite is partly converted into maskelynite around the shock veins. The veins are composed of spherical Fe-sulfide, rounded silicate fragments, and interstitial glass. No high-pressure phases are found in them. Although the Ar-Ar age spectra of these three meteorites are partly disturbed, Ar gases extracted from moderate- to high-temperature steps yield Ar-Ar ages of 3.835±0.007, 4.420±0.010, and 4.208±0.012 Ga for Wellman (c), Salaices, and Ochansk, respectively.

The other meteorite, Seagraves (c) (L6/7), experienced stronger shock metamorphism compared with above H chondrites. Albite is completely maskelynitized throughout our thin section. A shock melt vein contains abundant high-pressure minerals, such as majorite-pyrope garnet and wadsleyite. Its Ar-Ar age spectra are not completely but highly disturbed, indicating partial degassing. While three low-temperature steps yield ~1.6 Ga in average, the Ar-Ar ages gradually become older up to 4.15 Ga as increasing the heating temperature.

Discussion

The Ar-Ar age is not completely disturbed in Seagraves (c) despite its stronger shock metamorphism. This result may imply that a relatively recent shock event such as ~1.6 Ga can only induce a temporal temperature increase because such collisions are likely to happen between "cold" bodies, and the heated areas are cooled immediately. Since enormous energy is needed to heat the entire bodies, the complete reset of Ar-Ar ages is not easily attained by such cold bodies' collisions (e.g., Stephan and Jessberger 1992). In contrast, high-pressure minerals may only form/survive in such severe collisions between low-temperature bodies. Most L chondrites containing high-pressure minerals certainly show younger Ar-Ar ages, in particular around 500 Ma (e.g., Swindle et al. 2014), although the reason why only L chondrites among ordinary chondrites tend to have experienced recent-severe collisions is still unknown.

The Ar-Ar ages of 3.84-4.42 Ga in moderate- to high-temperature steps in three H chondrites (Wellman (c), Salaices, and Ochansk) are significantly younger than their thermal metamorphic ages (>~4.46 Ga). Thus, these Ar-Ar ages should represent thermal events induced by asteroidal collisions. Since shock metamorphic textures in these H chondrites are not significant, most collisional events >3.84 Ga may induce low shock-pressure but high-temperature (e.g., Ruzicka et al. 2015). Such conditions could be attained by collisions between hot bodies heated via radioactive decay or by frequent and/or large-scaled collisions (burial in a thick ejecta blanket). Alternatively, collision to a porous body can generate high-temperature with low shock-pressure. When Ar-Ar ages are completely reset up to high-temperature steps, the high-temperature may also erase parts of shock metamorphic textures, such as glassy veins and mineral cracks. Therefore, the thin glassy veins observed in the three H chondrites formed during weak shock events later than the high-temperature shock events at 3.84-4.42 Ga. This result may indicate that only weak collisional events that do not disturb Ar-Ar systems proceeded on the parent body(ies) of H chondrites after 3.8 Ga.

The two meteorites without shock features (Nuevo Mercurio and Ozona) show remarkably old Ar-Ar ages. Although these ages are likely to represent the thermal metamorphic ages of chondrites, there is still another possibility that these ages are modified by early shock-induced thermal events (e.g., Dixon et al. 2004) which also erased apparent shock metamorphic features by post shock annealing. In this case, the healed cracks and Fe-sulfide trails could be evidence of previous shock metamorphism (e.g., Rubin 2002). However, we need to analyze more samples to reveal chondrites' collisional histories in the solar system.

Conclusion

In the early solar system until 3.8 Ga, shock events commonly induced high shock-temperature and easily reset Ar-Ar ages because asteroids may be still hot due to heating via radioactive decay or by frequent and/or large-scaled collisions, or because asteroid collided to porous materials. After that, although severe shock events enough to induce high-pressure minerals can (partly) reset Ar-Ar ages, weak shock events hardly disturb Ar-Ar system, and we cannot determine their shock ages by Ar-Ar chronology. In contrast, high-pressure minerals can only form/survive during such recent-severe shock events between cold bodies. To reveal more detailed collisional histories of asteroids, we need to analyze more samples, such as H chondrites with high-pressure minerals (e.g., Yamato-75100).

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