Visualization of Reversible Shock Dynamics of Baddeleyite

Baddeleyite (ZrO_2) is a commonly found mineral on the Earth, Moon, Mars, and meteorites. The phase transition in this mineral can be employed as a shock pressure barometer and geochronometer of impact events. In this study, we investigated the phase transformation dynamics of baddeleyite through shock experiments using synchrotron time-resolved X-ray diffraction measurements. The results show that baddeleyite transforms to the high-pressure orthorhombic-I phase at 3.3 GPa during shock compression but immediately transforms back to the baddeleyite phase upon decompression. The results can be used to estimate the scale of past planetary impact events.

Meteorite impact events, such as that which led to the mass extinction dinosaurs, have caused catastrophic phenomena on Earth. Accurate dating and estimation of the scale of impact events are vital for understanding their history. The impact history can be recorded in rocks on the Earth's surface as "shock metamorphism" of minerals.

ZrO_2 (baddeleyite) is one of the minerals that can be used as an impact indicator. It is a common accessory mineral in rocks on the Earth, Moon, and Mars and in meteorites. Because of the high quantities of uranium as a trace element and the high resistance to weathering processes, uranium–lead dating of baddeleyite can be used as a chronometer of past impact events. To use it as an accurate chronometer, it is crucial to understand the shock behavior of baddeleyite.

In this article, we report on an experimental study on the dynamic behavior of baddeleyite under impact-induced shock [1].

Baddeleyite at natural impact sites

Previous studies on the observation of baddeleyite at natural impact sites revealed that it exhibited grain refinement resulting from high-pressure shock loading [2, 3]. Although the samples did not exhibit the crystal structure of a high-pressure phase, the deformed baddeleyite grains did have a certain orientational relationship, which can be caused by the transformation to the high-pressure phase and subsequent reversion to baddeleyite [3]. However, the dynamics has never been observed directly, and the exact behavior is unclear. If the crystal response to shock loading is confirmed and the shock pressure of the phase transition boundary is determined, the microstructure of the baddeleyite can be used as an accurate indicator of past impact events. Therefore, we experimentally investigated the crystal structure response to shock loading.

How do we examine the crystal structure response to shock loading?

Conventional shock experiments, such as shock-wave velocity measurements and shock recovery experiments, enable estimation of the shock dynamics of materials. However, these methods lack real-time crystal structure information. In this study, to observe the change in crystal structure during a shock, a high-power laser and synchrotron X-rays were used as a shock-driving source and a probe source, respectively. The experimental system was established at the AR-NW14A beamline [4]. The shock-loading condition was generated by irradiation with a laser pulse. The X-ray diffraction (XRD) image, which reveals the crystal structure during the shock, was captured by a synchrotron X-ray pulse. Capturing XRD images at different delay times (on a nanosecond time scale) for the same targets provides the time evolution of the crystal structure (Fig. 1).

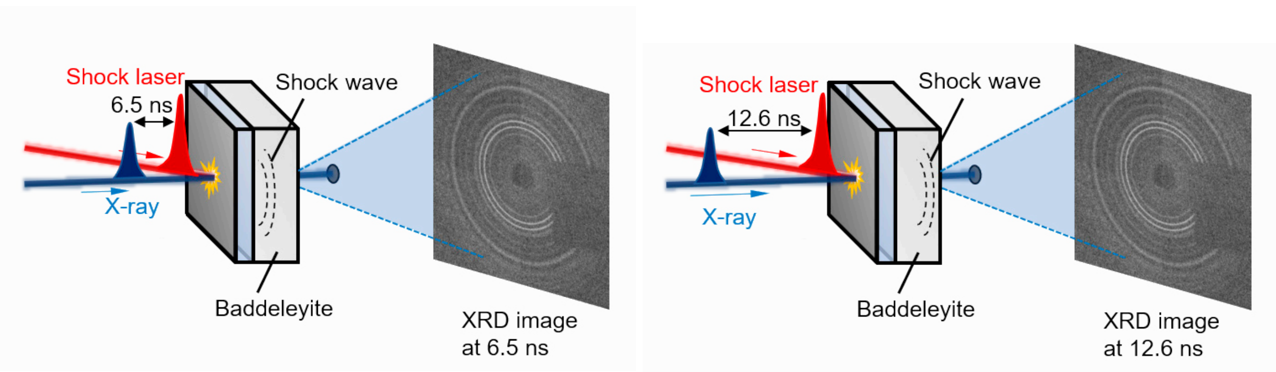

Figure 1: Configuration of the shock experiment at the AR-NW14A beamline. The irradiation timing of the laser pulse for generating the shock wave and X-ray pulse for detecting the crystal structure was controlled on a nanosecond time scale.

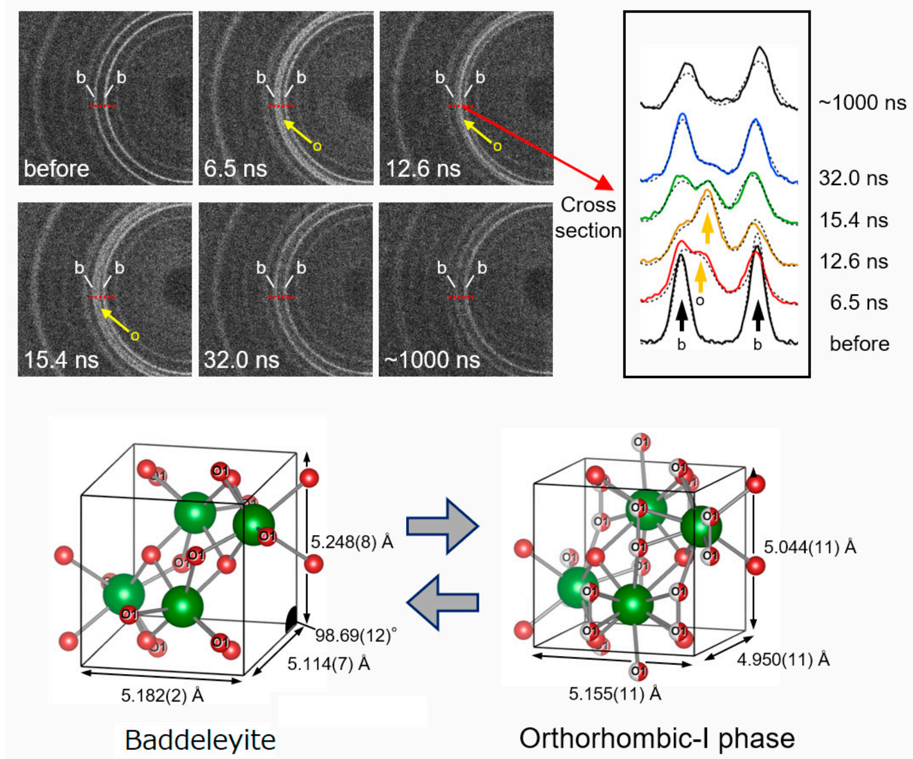

Figure 2: Time evolution of XRD pattern under the shock-loading condition and the crystal structure change. (Upper part) "b" and "o" represent the XRD rings from baddeleyite and the orthorhombic-I phase, respectively. The orthorhombic-I phase appeared between 6.5 and 15.4 ns after the onset of shock compression and disappeared after the shock released. (Lower part) The crystal structure reversibly changed between baddeleyite and the orthorhombic-I phase during the shock event.

Transformation dynamics

Figure 2 (upper part) shows the time evolution of the XRD patterns. Before the shock, the XRD rings from baddeleyite (labeled "b") were clearly observed. At 6.5 ns, after the onset of shock compression, a new XRD ring (labeled "o") appears. This ring can be attributed to the signal of the high-pressure phase (orthorhombic-I phase). The signal of the orthorhombic-I phase increases until 12.6 ns, but then it gradually decreases. Finally, the XRD pattern returns to that of baddeleyite at ~1000 ns. This result indicates that the crystal structure changed from baddeleyite to the orthorhombic-I phase during compression and that the orthorhombic-I phase reverted to baddeleyite during the release of the shock (Fig. 2, lower part). By using the density calculated from the XRD pattern, the pressure boundary of the transformation was determined to be 3.3 GPa.

In this experiment, the change in the crystal structure of shocked baddeleyite was directly observed using the time-resolved synchrotron XRD method. It was revealed that the transformation from baddeleyite to the orthorhombic-I phase occurs at 3.3 GPa and it reverts to baddeleyite during shock release. This is the first time that the reversible behavior of a mineral's crystal structure was directly clarified experimentally. This phenomenon cannot be observed using conventional experimental techniques. This information can be used by geologists to estimate the scale of past impact events and a planet's bombardment history using natural baddeleyite samples.

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BEAMLINE

AR-NW14A

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