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Response of a mineral to short time shock loading

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【Abstract】

A laser shock experiment at SACLA has been conducted on the mineral zircon by a research group led by Sota Takagi at the Institute for Materials Structure Science of the High Energy Accelerator Research Organization (KEK) in collaboration with the University of Tsukuba, Osaka University, RIKEN, and JASRI.

Crystal structure dynamics was observed using a bright XFEL pulse during the nanosecond timescale of a laser-driven shock. A phase transformation to high-pressure reidite was observed, but decomposition of zircon ($ZrSiO_4$) to SiO_2 and ZrO_2 was not observed. The result is different from the phase dynamics when the mineral is exposed to high pressure and high temperature for a long time. The time effect on mineral dynamics was demonstrated in this study.

The results were published in the journal *Physics and Chemistry of Minerals* on May 3rd, 2022.

【Background】

Zircon ($ZrSiO_4$) is a mineral that is widely found in rocks and meteorites on Earth. Some of you may know it as a gemstone. Zircon has an important role as a “clock” because the uranium contained in trace amounts changes to lead over a geological time of several billion years. Experiments have shown that the crystal structure changes to reidite in the high-pressure phase and decomposes to oxides (ZrO_2 and SiO_2) depending on temperature and pressure. By observing the traces left by these changes in natural zircon, we can estimate what temperatures and pressures the zircon was exposed to in the past, and the time that has passed since crystallization from magma or a meteorite collision.

In previous studies, the crystal structure dynamics was investigated when zircon was exposed to high temperatures and pressures for a long time. However, a meteorite impact-induced shock only causes high temperature and high pressure for a moment. Therefore, the crystal structure change, and decomposition under the impact is difficult to observe even with experiments and has not been clarified.

【Research and results】

In this study, we performed a laser shock experiment at SACLA(*1), the X-ray Free Electron Laser Facility in Japan, to observe the crystal structural dynamics of zircon during shock. The technique generates a shock wave by irradiating a sample with intense laser pulses, and the crystal structure changes before, during, and after the shock are photographed using a bright X-ray pulse (Fig. 1). The sample was a sintered zircon with a length and width of 5 mm and a thickness of 50 micrometers. This zircon was irradiated with an intense laser pulse with a time width of 5 nanoseconds (5 billionths of a second), and was irradiated simultaneously with the X-ray pulse to obtain X-ray diffraction images.

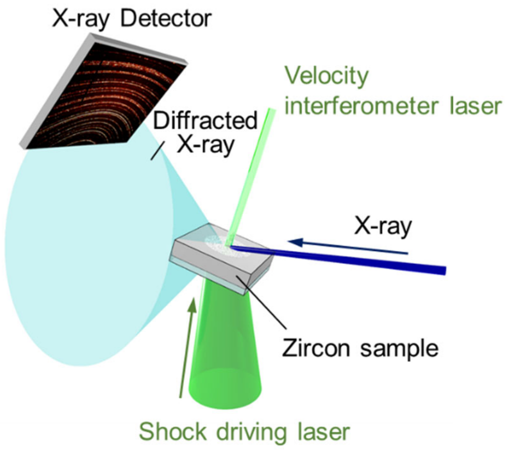

Fig. 1: Configuration of the laser shock experiment.

Figure 2 shows the X-ray diffraction images and spectra. The X-ray diffraction spectra reflect the crystal structure, and the crystal structure can be determined from the pattern. The diffraction peaks of the high-pressure phase, reidite, can be observed at a laser pulse energy above 3.1 J. At 10.3 J, the material melted at a pressure of about 70 GPa and temperature of 2000 °C, and the X-ray diffraction peaks of crystals disappeared. The X-ray diffraction image of the shock release process shows that the material crystallized again and returned to a mixed state of zircon and reidite.

During the laser impact, a phase transition to reidite was observed, but no decomposition was observed. This is different from the results of previous experiments conducted under high temperatures and high pressures for a long time, and suggests that decomposition is unlikely to occur in a short time with a laser-induced shock.

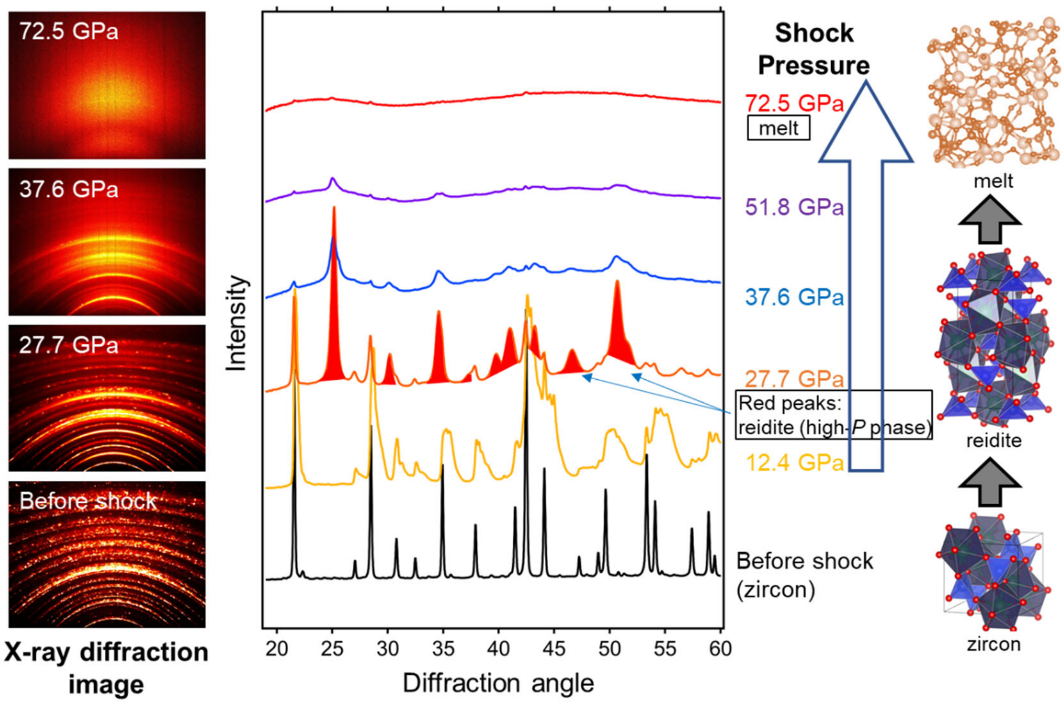

Fig. 2: X-ray diffraction data for a laser-induced shock.

【Significance of this research and future outlook】

The crystal structure of minerals changes depending on the surrounding temperature and pressure. Capturing in detail the phenomena that occur in a very short time, as in this study, has made it clear that time is also a factor in the crystal structure change. In the future, we aim to describe the changes in crystal structure when temperature and pressure are changed on various time scales, and to obtain data that will be useful for estimating the exact scale of meteorite impacts in the past.

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【Glossary】

*1. SACLA: SPring-8 Angstrom Compact free electron LAser

The first X-ray Free Electron Laser (XFEL) facility in Japan, jointly constructed by RIKEN and JASRI. The construction was completed in March 2011. The first X-ray laser beam was emitted at SACLA in June 2011, and the facility has been in operation since March 2012. Despite its compact size compared with facilities in other countries, SACLA is capable of producing XFEL beams with wavelengths of 0.055 nanometers or less.

【About Institutions】

High Energy Accelerator Research Organization (KEK)

KEK was established to promote various types of research as a center of excellence for overall development of Japan’s accelerator science (particle and nuclear research using high energy accelerators, research on the structure/function of matter including living organisms, research on improving accelerator performance, and related basic technologies). Under the Inter-University Research Institute Corporation, KEK provides researchers across the country and abroad with opportunities for research. With the Tsukuba and Tokai campuses as centers for

excellence, KEK joins international collaboration experiments and developments. In addition, as a research organization under the Graduate University for Advanced Studies, KEK fosters scientists who will contribute to accelerator science and advanced research fields.
https://www.kek.jp/en/

The University of Tsukuba

The University of Tsukuba is located in the suburbs of Tokyo and is at the heart of Tsukuba Science City —Japan's largest "science city," which has 29 national research institutes and about 150 private research organizations. The University operates on the principle that it is open to all.

The University of Tsukuba aims to cross the borders that separate a variety of organizations, such as those between nations, research institutions, and fields of study. The University's network is expanding globally. In particular, the University has entered into ten campus-in-campus arrangements with universities in eight countries and regions, thereby promoting close cooperative relationships between education and research. At present, the University hosts approximately 2,200 study abroad students from more than 110 countries and regions.
https://www.tsukuba.ac.jp/en/

Osaka University

Osaka University was founded in 1931 as one of Japan's imperial universities through strong demand from political and business circles in Osaka, as well as the people of Osaka City and Prefecture. The spiritual roots of Osaka University can be found in Kaitokudo and Tekijuku, educational institutions of the Edo period. After its merger with Osaka University of Foreign Studies in 2007, Osaka University became a comprehensive university with its own School of Foreign Studies. Boasting 11 undergraduate schools, 15 graduate schools, and 6 affiliated research institutes excelling in the fields of the humanities and social sciences, medicine, dentistry, pharmacy, science, and engineering, Osaka University is one of Japan's premier comprehensive research universities.

Osaka University, which will celebrate the 100th anniversary of its founding in 2031, will strive to be a world-leading innovative university that contributes to social change under its motto of "Live Locally, Grow Globally."
https://www.osaka-u.ac.jp/en

RIKEN

RIKEN is Japan's largest research institute for basic and applied research. Over 2500 papers by RIKEN researchers are published every year in leading scientific and technology journals covering a broad spectrum of disciplines including physics, chemistry, biology, engineering, and medical science. RIKEN's research environment and strong emphasis on interdisciplinary collaboration and globalization has earned a worldwide reputation for scientific excellence.
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Japan Synchrotron Radiation Research Institute (JASRI)

JASRI is a public interest incorporated foundation in charge of the operation, maintenance, management, and provision of support for users of the SPring-8 synchrotron radiation facility, as well as the provision of support for users of the X-ray free electron laser SACLA. JASRI is a highly professional, advanced, interdisciplinary, and international institute.

http://www.jasri.jp/en/index.html