Melt-mediated re-equilibration of zircon produced during meltdown of the Chernobyl reactor

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ABSTRACT

The mineral zircon is used widely to constrain the age of rocks and the processes that formed them. Although zircon is robust to a range of physical and chemical processes, it may show evidence for rapid re-equilibration that is generally considered to reflect interaction with hydrous fluids. Here, we show that zircon grains that crystallized from melt produced during the catastrophic meltdown of the Chernobyl nuclear reactor exhibit re-equilibration textures that occurred in an environment without free water. The process of re-equilibration involved a melt-mediated interface-coupled dissolution–reprecipitation that took place over a few days to produce textures that are commonly observed in igneous and anatectic systems. Thus, the composition of zircon can be modified even in the absence of hydrous fluids in a short time frame. Through this process, zircon crystals may track the timing of the last silicate melt they interacted with.

Keywords: Zircon, anatexis, nanoscale, atom probe tomography, re-equilibration; Isotopes, Minerals, and Petrology: Honoring John Valley

INTRODUCTION

The catastrophic meltdown of the reactor 4 of the Chernobyl Nuclear Power Plant on April 26, 1986, is the worst nuclear disaster in history. The reactor experienced a suite of unexpected events causing an uncontrolled nuclear chain reaction (Müller 2019). The temperature reached in excess of 2600 °C, causing the uranium fuel rods and their zirconium alloy cladding to melt and drop at the bottom of the reactor (Burakov et al. 1996). This molten material, or corium, dissolved constituents of the reactor, including steel, concrete, serpentine, and sand, evolving to a silicate melt from which zircons [ZrSiO4] crystallized at a temperature below 1250 °C (Burakov et al. 1996; Pätzolin 1994; Pöml et al. 2013; Ushakov et al. 1996).

Zircon is a commonly used mineral to understand when and how rocks formed (Harley and Kelly 2007). Despite its chemical and physical robustness, the internal structure of zircon grains can be chaotic and indicates that zircon may partially re-equilibrate in response to changing pressure-temperature-composition (P-T-X) conditions (Martin et al. 2008; Rubatto 2017). To this day, hydrous fluids are believed to play an important role in modifying particular domains within zircon, especially if they have been damaged by radioactive decay (Geisler et al. 2003, 2007). However, similar features are also recorded in crystalline zircon grains from metamorphic environments (Rubatto et al. 2008) or due to interaction with high-T magmatic fluids (Soman et al. 2010). Re-equilibration textures in zircon have also been documented from various settings in which hydrous fluids likely played little or no role, including igneous (Bindeman and Melnik 2016; Gagnevin et al. 2010), high-grade metamorphic (Hoskin and Black 2000; Zheng et al. 2004), and experimental systems (Tomascheck 2004). Although several mechanisms have been proposed to drive re-equilibration of zircon in fluid-deficient settings, including solid-state recrystallization (Hoskin and Black 2000) and melt-mediated interface-coupled dissolution–reprecipitation (Geisler et al. 2007), such mechanisms are poorly understood.

Chernobyl zircon grains, collected during an inspection of the Power Plant in 1989 are well suited to study the re-equilibration of a crystalline zircon in an anhydrous melt (Shiryaev et al. 2016). Although some of the Chernobyl melt interacted with water to form porous ceramics in localized areas of the plant where water was pooling, the majority of the melt was never in contact with water thanks to the rescue team that drained the flooded basement, avoiding another, larger catastrophe. The Chernobyl melt remained at atmospheric pressure during its evolution and, therefore, could only dissolve negligible water (Carroll and Blank 1997; Dixon et al. 1995; Silver et al. 1990). The Chernobyl zircons contain high-U contents, however they are virtually free of damage due to internal radioactive decay. Here, we investigate the textural and chemical features of one of these zircon grains using crystallographic orientation mapping, ion imaging, and nanoscale analyses, with the aim of determining the mechanisms of zircon re-equilibration in a dry magmatic setting.

SAMPLE AND METHODS

At Chernobyl, several types of lava-like solidified materials have been described such as the black and brown silicate glass as well as porous ceramics that formed by