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Shock-deformed zircon from the Chicxulub impact crater and implications for cratering process

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ABSTRACT

Large impact structures with peak rings are common landforms across the solar system, and their formation has implications for both the interior structure and thermal evolution of planetary bodies. Numerical modeling and structural studies have been used to simulate and ground truth peak-ring formative mechanisms, but the shock metamorphic record of minerals within these structures remains to be ascertained. We investigated impact-related microstructures and high-pressure phases in zircon from melt-bearing breccias, impact melt rock, and granitoid basement from the Chicxulub peak ring (Yucatán Peninsula, Mexico), sampled by the International Ocean Discovery Program (IODP)/International Continental Drilling Project (IODP-ICDP) Expedition 364 Hole M0077A. Zircon grains exhibit shock features such as reidite, zircon twins, and granular zircon including "former reidite in granular neoblastic" (FRIGN) zircon. These features record an initial high-pressure shock wave (>30 GPa), subsequent relaxation during the passage of the rarefaction wave, and a final heating and annealing stage. Our observed grain-scale deformation history agrees well with the stress fields predicted by the dynamic collapse model, as the central uplift collapsed downward-then-outward to form the peak ring. The occurrence of reidite in a large impact basin on Earth represents the first such discovery, preserved due to its separation from impact melt and rapid cooling by the resurging ocean. The coexistence of reidite and FRIGN zircon within the impact melt–bearing breccias indicates that cooling by seawater was heterogeneous. Our results provide valuable information on when different shock microstructures form and how they are modified according to their position in the impact structure, and this study further improves on the use of shock barometry as a diagnostic tool in understanding the cratering process.

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INTRODUCTION

Impacts generate various types of crater forms (e.g., simple, central-peak, peak-ring, and multiring morphologies) on rocky and icy planetary bodies. Peak-ring and multiring impact structures are rarely preserved on Earth due to tectonic activity, erosion, and volcanic resurfacing (Osinski and Pierazzo, 2012). The best-preserved peak ring on Earth is the Chicxulub ring structure (Yucatán Peninsula, Mexico), where it was imaged with seismic reflection data and shown to directly overlie sedimentary rocks (Gulick et al., 2008). The seismic images were used to "ground truth" numerical simulations, which led to the dynamic collapse model being proposed as a mechanism for the formation of peak rings. In this model, overshooting central uplifts collapse downward and outward, overthrusting the collapsing shallow target materials from transient crater walls (Morgan et al., 2000). Subsequently, support for this model was obtained from macroscopic observations in drill core recovered during International Ocean Discovery Program (IODP)/International Continental

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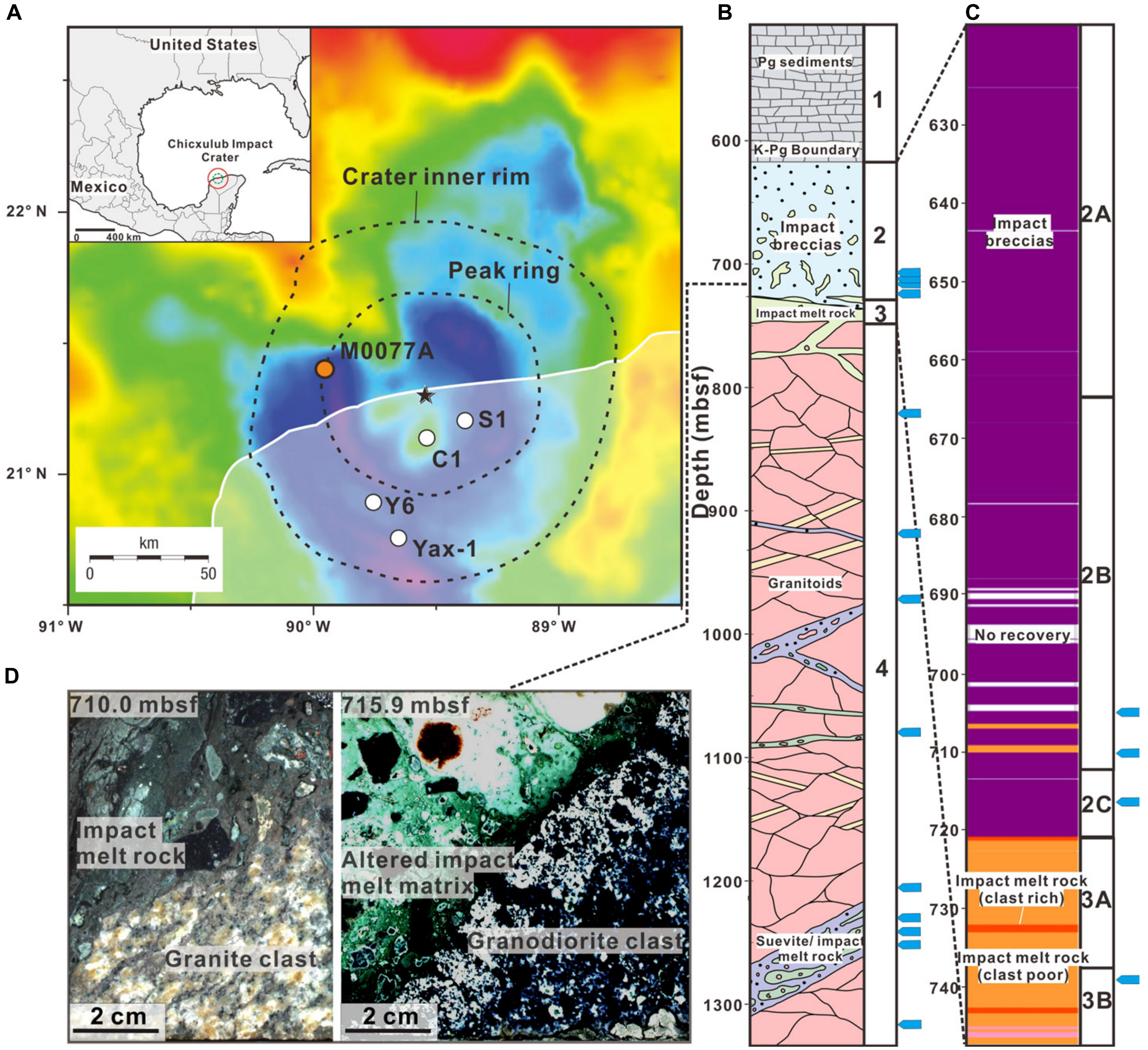

Figure 1. (A) Location of the Chicxulub impact crater (Gulick et al., 2008). (B) Lithology of International Ocean Discovery Program (IODP)/ International Continental Drilling Project (IODP-ICDP) Expedition 364 Hole M0077A (Morgan et al., 2016) and sample sites (blue arrows). mbsf—meters below seafloor; K-Pg—Cretaceous-Paleogene. (C) Detailed lithology of stratigraphic units 2 and 3 (Morgan et al., 2017). (D) Photos of impact melt–bearing breccia, including granite clast ("former reidite in granular neoblastic" [FRIGN] zircon) with impact melt matrix and granodiorite clast (reidite) with altered impact melt matrix.

Drilling Project (IODP-ICDP) Expedition 364 (Morgan et al., 2016; Riller et al., 2018; Collins et al., 2020). Based on samples from Hole M0077A, extensive studies have been reported on shock metamorphism of quartz, titanite, and apatite from the granitoid basement that makes up the Chicxulub peak ring (Rae et al., 2017; Timms et al., 2019, 2020; Cox et al., 2020; Feignon et al., 2020). Zircon is an accessory mineral that is particularly useful for dating and can also display shock-effect indicators, such as planar fractures (PFs), {112} twins, reidite, granular zircon, and dissociation (Cavosie et al., 2015b; Timms et al., 2017). Until now, reidite has only been observed in simple and central-peak impact craters, such as Chesapeake Bay (northeastern USA), Haughton (Canada), Ries (Germany), Rock Elm (northeastern USA), Woodleigh (Western Australia), and Xiuyan (China) (Wittmann et al., 2009; Chen et al., 2013; Cavosie et al., 2015a; Erickson et al., 2017; Cox et al., 2018). It is a puzzle as to why no reidite has previously been found within larger craters (e.g., the Chicxulub, Vredefort [South Africa], and Sudbury [Canada] impact structures), which should, in theory, contain larger volumes of materials shocked above threshold pressures of >30 GPa (Cavosie et al., 2018). Drill cores recovered during IODP-ICDP Expedition 364 display an unprecedented record of brittle and crystal-plastic deformation within the peak-ring rocks and shed light on the peak-ring formation processes (Riller et al., 2018). However, so far, only small numbers of zircon grains from this drill core have been studied, some of which

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display shock features such as twins and "former reidite in granular neoblastic" (FRIGN) zircon (Timms et al., 2019; Cox et al., 2020).

In this study, we documented the microstructures and their formation sequence in zircon extracted from different sites (melt-bearing breccias, impact melt rock, and granitoid basement) in the Chicxulub impact structure. In addition, we discuss the significance of our data and modeling with respect to cratering processes.

SAMPLES AND METHODS

Core samples were obtained from IODP-ICDP Expedition 364 Hole M0077A, which was drilled into the peak ring of the Chicxulub impact structure. Four main stratigraphic units were encountered; from top to bottom, these were: Cenozoic sediments (unit 1), impact melt–bearing breccia (unit 2, also referred to as "suevite"), impact melt rocks (unit 3), and granitoid basement that contains pre-impact felsic and mafic dikes and synimpact melt-bearing breccia intercalations (unit 4; Morgan et al., 2017). We chose 13 fragments of felsic samples from the impact melt–bearing breccias, impact melt rock, and the granitoid basement for this study (Fig. 1). In total, 1739 zircon grains were extracted from these samples, mounted in epoxy, and polished for analysis. Backscattered-electron (BSE), cathodoluminescence (CL), and orientation contrast (OC) imaging, Raman spectroscopy, and electron backscatter diffraction (EBSD) mapping were used to analyze the morphology, deformation microstructures, and crystallographic relationships among phases in the zircon grains (Item S1 in the Supplemental Material[1]). An iSALE-2D (https://isale-code.github.io/) numerical simulation of the Chicxulub impact event was used to estimate the peak pressure and temperature of peak-ring materials (see the Supplemental Material).

RESULTS

Reidite lamellae in zircon from the granodiorite clast (715.9 m below seafloor [mbsf], unit 2C; Figs. 1 and 2A) were identified by Raman spectra peaks at 297 cm^{-1}, 461 cm^{-1}, 611 cm^{-1}, and 846 cm^{-1} (Fig. 2B). The reidite lamellae truncate some PFs and appear dark in CL images and pale in BSE images, with widths varying from ~0.2 to 2 μm (Figs. 2C–2E). The host zircon contains two to three sets of reidite lamellae, and some grains have up to five sets (456 grains; Tables S1 and S2). The host zircon and reidite lamellae have close alignment between one set of $\{112\}_{Zircon}$ and $\{112\}_{Reidite}$, and one set of $\{100\}_{Zircon}$ is aligned with one set of $\{112\}_{Reidite}$ seen in pole figures (Fig. 3A).

Shock twins have a 65°/<110> misorientation relationship with the host zircon in EBSD maps (~0.2–1.2 μm in width), and some of them were too fine to be indexed by EBSD (Fig. 3A). In zircon grains from granodiorite clasts and granitoid basement (715.9, 739.4, and 979.3 mbsf, units 2C, 3, and 4; Fig. 1; Tables S1 and S2), twins transected reidite lamellae, PFs, and planar deformation bands (PDBs) in single grains (Fig. 3A; Supplemental Material Item S2).

Granular zircon from the granite and granodiorite clasts (710.02 and 739.35 mbsf, units 3B and 2C; Tables S1 and S2) was partially or completely composed of zircon granules (1–5 μm) and zirconia (~0.2–2 μm; Fig. 3B; Supplemental Material Item S2). Typically, these granules exhibited three mutually orthogonal sets of orientation clusters. The (001) and (110) poles of these three orientation clusters are aligned with each other, and each cluster has a dispersion of lower than 40° seen in pole figures (Fig. 3B).

DISCUSSION

Formation Conditions of Reidite, Twins, and Granular Zircon

Two models have previously been proposed to explain the transformation of zircon to reidite: (1) reconstruction-induced transformation (Marqués et al., 2008), and (2) deviatoric stress–induced transformation (Kusaba et al., 1986; Erickson et al., 2017). The reidite lamellae observed in our study crosscut the PFs (~1 μm in width) with displacive features (Fig. 2C). These relationships suggest that deviatoric stress–induced shear appears to be a more plausible explanation for the transformation from zircon to reidite lamellae. In contrast, the reconstruction-induced model is inconsistent with our observations, since the resulting reidite would be expected to be granular in texture with granules nucleating under high pressure (Erickson et al., 2017). In terms of shock conditions, static experiments suggest reidite can be formed at 12–23 GPa, while the appearance of reidite in shock experiments requires pressures of >30 GPa (Timms et al., 2017; Cavosie et al., 2018).

Twins optimally occur along the $\{112\}_{Zircon}$ planes in the direction of $<111>_{Zircon}$ with the lowest values of shear modulus (Timms et al.,

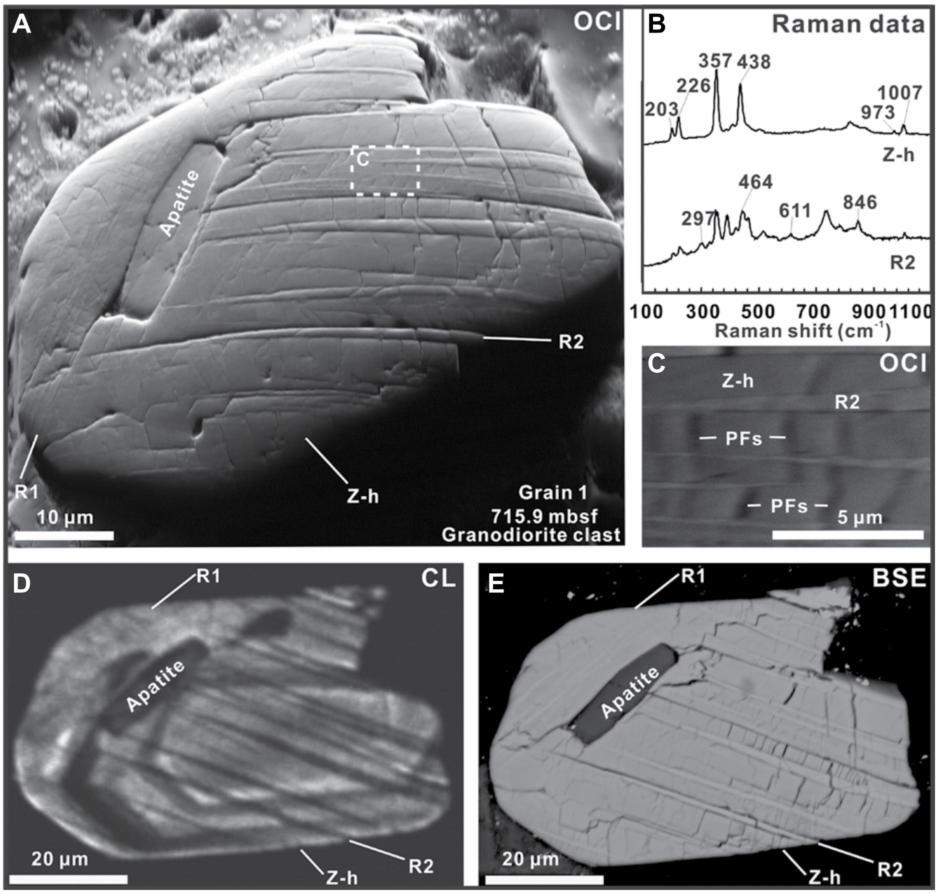

Figure 2. Reidite lamellae in zircon from granodiorite clast (715.9 m below seafloor [mbsf], grain 1). (A) Forescatter orientation contrast image (OCI), Z-h—zircon host; R1, R2—reidite. (B) Results of Raman spectra analyses. (C) Close-up of the OCI. PFs—planar fractures. (D) Cathodoluminescence (CL) image. (E) Backscattered-electron (BSE) image.

[1]Supplemental Material. Additional details on the methods (Item S1), summary of EBSD mapping results (Table S1), shock effects in zircon from different depths (Table S2), and zircon data from different depths (Item S2). Please visit https://doi.org/10.1130/GEOL.S.14079968 to access the supplemental material, and contact editing@geosociety.org with any questions.

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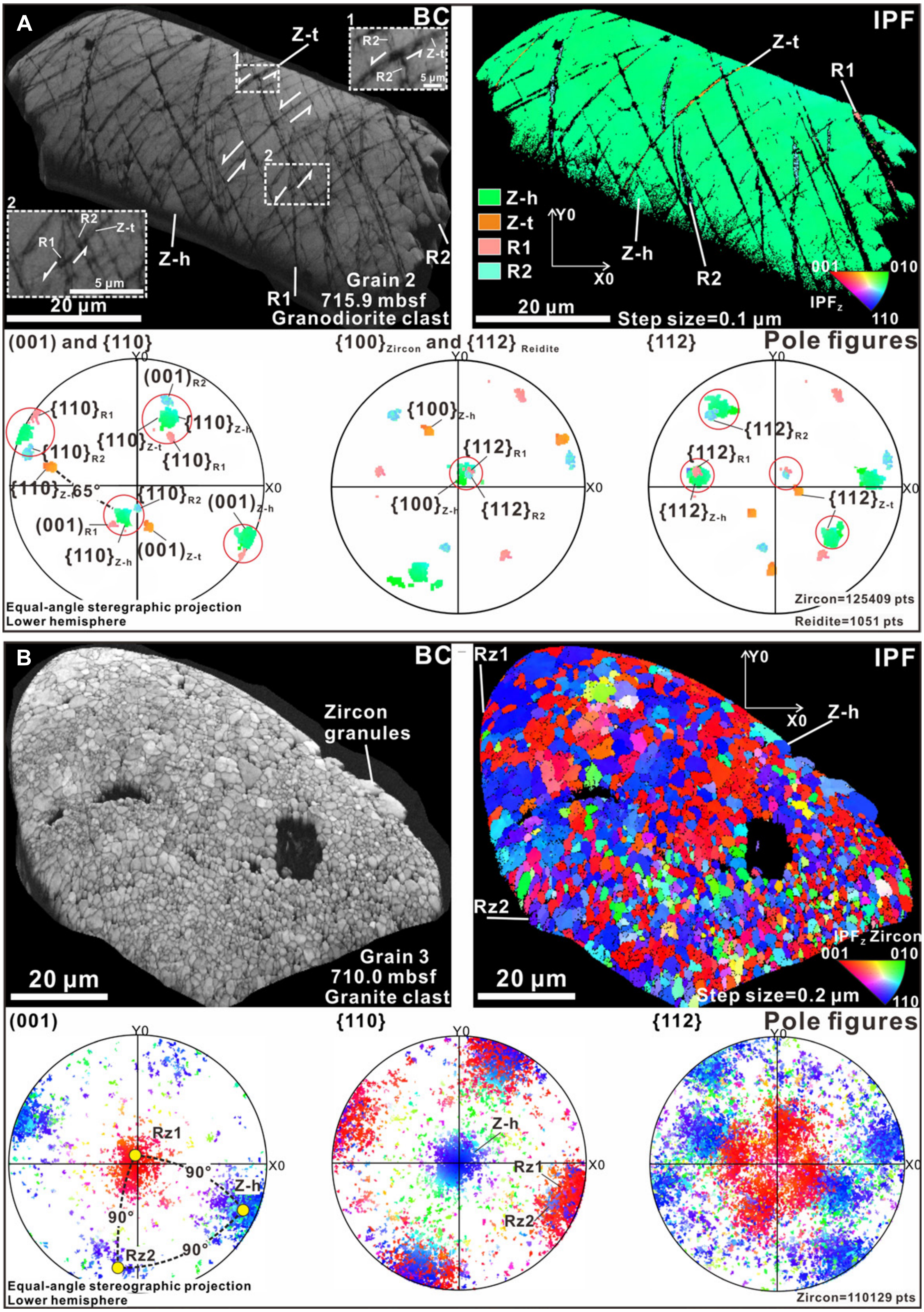

Figure 3. Features of reidite lamellae, shock twins, and "former reidite in granular neoblastic" (FRIGN) zircon. (A) Reidite- and microtwin-bearing zircon from granodiorite clast (715.9 m below seafloor [mbsf], grain 2). Z-h—zircon host; Z-t—zircon twins; R1, R2—reidite; BC—band contrast; IPF—inverse pole figure, where areas 1 and 2 are the close-ups of the crosscutting relationship between reidite and twins, shear direction is marked in arrows, and overlapped regions in the pole figures are marked as red solid circles. (B) FRIGN zircon from granite clast (710.0 mbsf, grain 3). Rz1, Rz2—reverted zircon.

2018). This is supported by the observation that the twins sinistrally truncate the reidite lamellae (Fig. 3A) and PDBs (Supplemental Material Item S2). Thus, shear stress was likely a contributing factor in the formation of the twins. Twins in zircon were also observed in the granitoid basement, where peak shock pressures have been estimated to range from 12 to 17 GPa using shock metamorphic features in quartz and titanite (Rae et al., 2017; Timms et al., 2019; Feignon et al., 2020). This is consistent with our results for the frequency of zircon with PFs from granitoid basement (10%–30%, 10–20 GPa; Table S2; Wittmann et al., 2006). Integrating pressure estimations based on static loading experiments and natural occurrences of twins in zircon (Moser et al., 2011; Cavosie et al., 2016; Morozova et al., 2017; Cox et al., 2018), the shock pressure that produced the twinning was ∼20 GPa.

Granular zircon is considered to be a high-temperature product that forms during or after

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shock decompression (Timms et al., 2017). Three mutually orthogonal orientation clusters of granular zircon exhibited the relationship of zircon-to-reidite transformation with the alignment of (001) and {110} (Fig. 3B), representing the reversion of reidite. The co-occurrence of FRIGN zircon and zirconia indicates a shock pressure >30 GPa and a postshock temperature >1673 °C (Cavosie et al., 2018).

Implications for Cratering Process

The occurrence of reidite- and twin-bearing zircon and FRIGN zircon suggests shock pressures >30 GPa in the felsic clasts of the impact melt–bearing breccias. This is compatible with the shock conditions and cratering process predicted by numerical simulations (Figs. 4A–4C; Morgan et al., 2016; Rae et al., 2019). Based on our results, we can establish the time line for the formation of various shock effects in zircon during the Chicxulub impact event: First, reidite was formed during the propagation of the shock wave, where shock pressures in the basement rocks exceeded 30 GPa. The shock wave was closely followed by a rarefaction wave, which facilitated the formation of the zircon twins via shear stresses during decompression (∼20 GPa; Figs. 4C and 4D; Melosh, 1989; Moser et al., 2011; Cox et al., 2018). This sequence is supported by the observation of a crosscutting relationship between the reidite and twins (Fig. 2A). Felsic clasts could be parautochthonous fragmented basement materials that became entrained in the melt-bearing breccias as the central uplift collapsed to form the peak ring (Gulick et al., 2019), similar to the process accounting for the co-occurrence of reidite and twins in zircon from basement materials in the central uplift of the Woodleigh structure (Cox et al., 2018). Alternatively, the felsic clasts could be allochthonous fragments that were remobilized when the ocean resurged into the crater causing explosive melt-water interactions (Gulick et al., 2019; Osinski et al., 2020).

Preservation of Reidite

Reidite has not been observed in previous studies of the largest terrestrial impact basins such as the Vredefort, the Sudbury, or the Chicxulub impact structures (Moser et al., 2011; Cavosie et al., 2018; Kovaleva et al., 2019). The formative processes of large impact craters create the conditions necessary to generate reidite, but an ambient temperature >1200 °C caused by initially superheated pools of melt is capable of destroying reidite via back-transformation to zircon (Kusaba et al., 1985; Cavosie et al., 2018). This is consistent with the observation that reidite is typically found in melt-poor breccias (Stöffler et al., 2013; Erickson et al., 2017), melt-poor ejecta (Glass et al., 2002), and basement rocks in the central or central peaks of impact structures

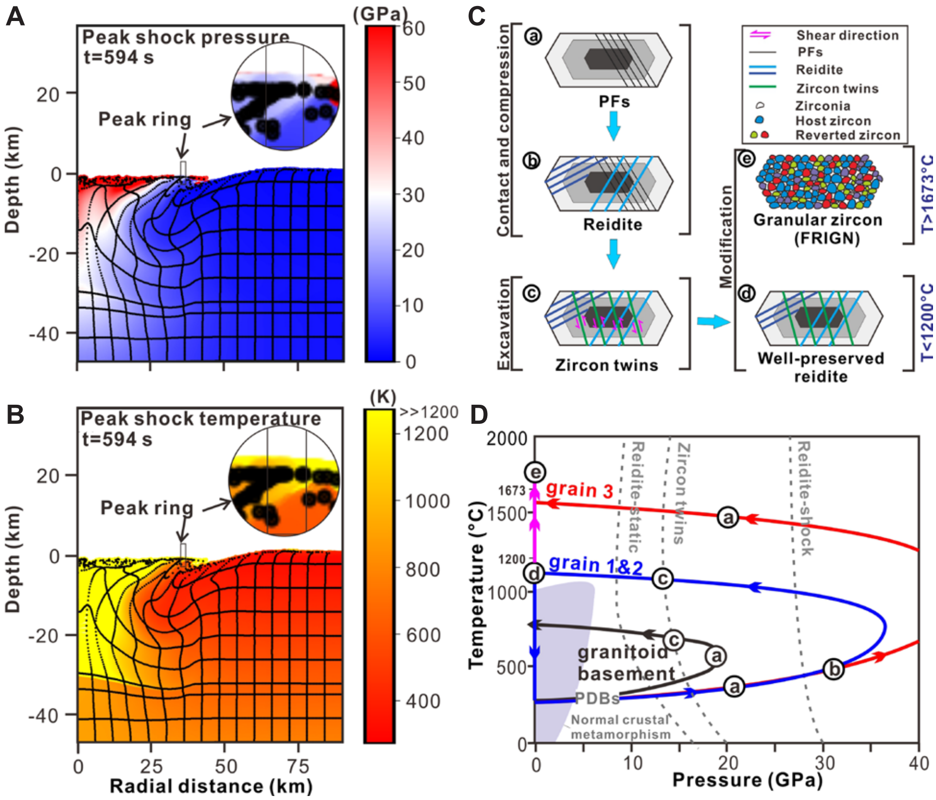

Figure 4. Simulation model and shock conditions in studied zircon grains. (A,B) iSALE-2D (https://isale-code.github.io/) impact simulations including peak shock pressure and temperature of peak-ring materials. (C) Formation sequence of shock microstructures in zircon. PFs—planar fractures; FRIGN—former reidite in granular neoblastic zircon. (D) Phase diagram for shock zircon (Morozova et al., 2017; Timms et al., 2017), including three paths for zircon grains 1 and 2 (blue line), grain 3 (red/blue + purple line), and zircon from granitoid basement (black line); symbols (a–e) in C are also shown in D. PDBs—planar deformation bands.

(Chen et al., 2013; Cox et al., 2018). In this study, FRIGN zircon and zircon containing reidite and twins were identified in the melt-bearing impact breccias, which occur immediately above an ∼20-m-thick layer of impact melt rock. Heating above 1673 °C (Figs. 4C and 4D, grain 3) due to the proximity of impact melt is thought to be the driver for the transformation from reidite-bearing zircon to FRIGN zircon (Cavosie et al., 2018; Cox et al., 2020). Moreover, a rapid and heterogeneous cooling mechanism is needed to preserve reidite (Figs. 4C and 4D, grains 1 and 2). Rapid cooling would occur if unit 2C were a product of highly energetic melt-water interactions, as suggested by Gulick et al. (2019) and Osinski et al. (2020). The observation that the matrix is dominated by highly altered glass, and the nonassimilation of the brecciated impact melt rock around the reidite- and zircon-bearing granodiorite clasts both support a heterogeneous cooling process during ocean resurge.

The formation sequence of microstructures in shocked zircon indicates different stages of the impact process, and the preservation and modification of these microstructures are closely related to their position in the impact structure. Therefore, the use of zircon as a shock indicator can uncover the continuity and heterogeneity of the impact processes.

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