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The formation of large neoblasts in shocked zircon and their utility in dating impacts

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ABSTRACT

Uranium-lead (U-Pb) geochronology of individual shocked zircon grains has unique potential for dating bolide impact events. Neoblasts in granular-textured zircon have been recognized as the shock-related feature most effective at recording the impact age. Here we report the discovery of large neoblasts (5–100 µm in dimension) in shocked zircon at the Sudbury impact structure, Canada—the first report of *in situ* coarsely granular zircon from a terrestrial impact site other than the Vredefort structure, South Africa. The neoblast-bearing sample was taken from a heterogeneous, lithic clast–rich igneous unit associated with the roof rocks of the impact melt sheet, making this the first time a crater has been dated using neoblastic zircon from the upper part of its stratigraphy. Previous *in situ* discoveries of coarsely granular zircon at Vredefort were all in impact-generated mafic melt emplaced beneath the impact melt sheet. Electron backscatter diffraction analysis of the impact-aged neoblasts indicates that the high-pressure conditions inferred in the formation of many small neoblasts were not necessarily involved in the formation of these large ones. Their large size, internal zonation, and occurrence in a slowly cooling environment collectively suggest that large neoblasts at Sudbury formed by relatively protracted, post-impact growth in shocked zircon incorporated into impact-related melt. Based on insight from large neoblast growth in terrestrial settings, we suggest that the ca. 4.33 Ga neoblasts recently reported in lunar zircon may imply a major basin-forming event on the Moon at that time. New knowledge of the cratering environments in which large neoblasts form also raises the prospect of possibly linking *ex situ* granular zircon in lunar breccias with specific impact structures—and thus better calibrating the lunar cratering record with radiometric ages.

INTRODUCTION

Uranium-lead (U-Pb) dating of individual shocked zircon grains has the potential to accurately date impact events and ultimately advance our knowledge of the impact record and geological evolution of the inner solar system.

While there are many impact-related features of shocked zircon (such as microtwins and the $ZrSiO_4$ polymorph reidite, both diagnostic of impact shock), low-strain neoblasts in granular-textured grains appear to have the best potential for recording the date of impact (Cavosie et al., 2015). Fine-grained neoblasts, generally <5 µm in dimension, are relatively common, having been reported from numerous impact environments including shocked target rock (Cavosie et al., 2016), impact melt (Kamo et al., 1996), lunar breccia (Grange et al., 2013), terrestrial impact-related breccia (Krogh et al., 1996), distal ejecta (Bohor et al., 1993), tektites (Deloule et al., 2001), and meteorites (Zhang et al., 2011). However, their small size means they are difficult to analyze and often suffer post-impact Pb loss, resulting in erroneously young dates (e.g., Krogh et al., 1993, 1996; Kamo et al., 1996, 2011; Schmieder et al., 2015). Cavosie et al. (2016) and Timms et al. (2017) have provided insight into the origin of small neoblasts via high-temperature and high-pressure impact-related processes. Larger neoblasts (5–100 µm in dimension) are rare but hold the best promise as an effective dating tool, being relatively easy to analyze and more likely to retain the impact age (Moser, 1997; Moser et al., 2011; Cavosie et al., 2015). They have previously been reported *in situ* from the Vredefort impact structure, South Africa (Moser, 1997; Moser et al., 2011), as well as *ex situ* from Vredefort (Cavosie et al., 2015), the Sudbury impact structure, Canada (Thomson et al., 2014), and lunar breccias (Crow et al., 2017). The two prominent granular zircon grains from Vredefort that were reported by Moser (1997; grain V58-1-Z5) and Moser et al. (2011; grain V09-232 G9) were both from noritic impact melts emplaced beneath the original impact melt sheet. The single neoblast-bearing zircon reported by Cavosie et al. (2015; grain 07VD07-3) was from a sample of modern alluvium, and the single zircon appearing to show "incipient recrystallization" at Sudbury (Thomson et al., 2014, p. 727; grain 10SU14-18) was from Holocene sand in an esker. Understanding the origin and significance of *ex situ* neoblast-bearing zircon grains, such as those in lunar breccias (Crow et al., 2017) or terrestrial sediments, requires a greater knowledge of how and where these features form in terrestrial impact sites and how they become preserved.

Here we report on the first discovery and analysis of *in situ* large neoblasts in shocked zircon at the Sudbury impact structure, Canada—the first such occurrence outside of Vredefort. Critically, this is also the first time that coarsely neoblastic zircon was discovered in the upper part of a crater's stratigraphy, it having been recovered from an igneous unit associated with the roof rocks of the impact melt sheet.

SAMPLES

Sample 13GGK029 was taken from a body of uneven-grained, lithic clast–rich granodiorite associated with the roof of the Sudbury impact melt sheet (Sudbury Igneous Complex). This sample belongs to the Onaping intrusions (e.g., Ames et al., 2005), which occur either as up to 300-m-thick, discontinuous, semi-conformable sheets at the contact between the Sudbury Igneous Complex and the overlying Onaping Formation breccias (Anders et al., 2015), or as individual bodies, up to ~500 m in maximum dimension, throughout the stratigraphy of the Onaping Formation. The former have recently been reinterpreted as the remains of the roof rocks of the impact melt sheet and not part of the Onaping Formation (Anders et al., 2015). Sample 13GGK029 was taken from the latter type of Onaping intrusion, specifically a ~25 × 50 m body from the Joe Lake area (Fig. 1).

ANALYTICAL METHODS

Following standard mineral separation procedures, the exteriors of zircon grains from sample 13GGK029 were imaged in backscatter electron (BSE) mode on a scanning electron microscope (SEM). The grains were then mounted in epoxy and polished to expose their interiors, which

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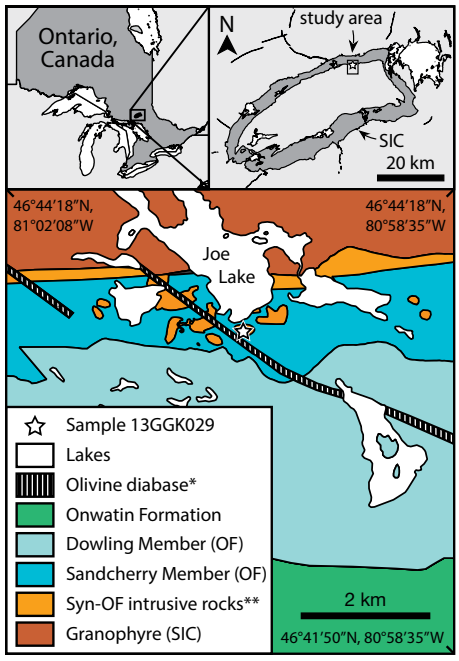

Figure 1. Map showing location of sample 13GGK029 at Sudbury impact crater (Ontario, Canada). Maps are modified after Ames et al. (2005). SIC—Sudbury Igneous Complex; OF—Onaping Formation. *—olivine diabase dikes belong to post-impact, ca. 1250 Ma Sudbury dike swarm. **—"syn-OF intrusive rocks" terminology of Ames et al. (2005); these include units previously mapped as "melt bodies" and Onaping intrusion, basal part of which has recently been reinterpreted as belong to SIC (see text, and Anders et al., 2015).

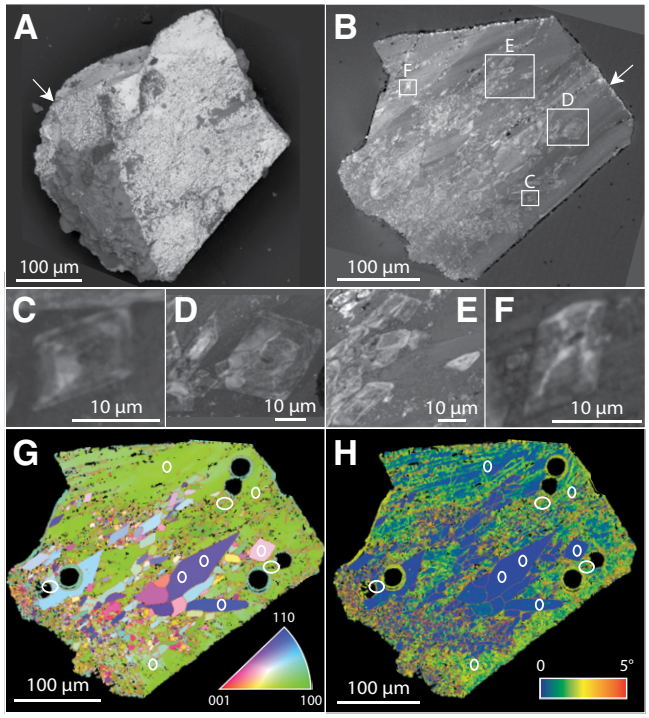

Figure 2. Imaging and electron backscatter diffraction analysis of granular shocked zircon 13GGK029-Z25 from Sudbury impact crater (Ontario, Canada). A: Backscattered electron image of grain exterior. Arrow points to surface on which polycrystalline nature of grain is readily visible. B: Cathodoluminescence (CL) image of polished grain interior. Arrow highlights CL-visible banding which may be original to grain prior to shock metamorphism. White boxes highlight areas shown in C–F. C,D: CL images of neoblasts appearing to show concentric internal structure. E: CL image showing internally complex neoblasts. F: CL image of neoblast appearing to show internal sector zoning. G: Map of zircon colored according to inverse pole figure scale, with all grain boundaries with misorientation >5° shown in red. H: Map of zircon showing degree of local misorientation (kernel average misorientation; see full analytical methods for details) with grain boundaries shown in red. White ellipses in G and H show locations of secondary-ion mass spectrometry U-Pb analyses. Black circular features in G and H represent laser ablation pits for rare earth element analyses not reported here.

were imaged in cathodoluminescence (CL) mode, also on an SEM. Full grain crystallographic orientation mapping was performed via electron backscatter diffraction (EBSD) analysis. For zircon U-Pb secondary-ion mass spectrometry (SIMS) analyses, the primary beam was operated in aperture illumination (Köhler) mode, yielding analysis pits ~15 µm (analyses a–c; see Table DR1 in the GSA Data Repository[1]) and 10 µm (analyses d–j) across. Full analytical methods can be found in the Data Repository.

RESULTS

Imaging

External BSE imaging of several hundred zircon grains from sample 13GGK029 documented shock-related features including planar microstructures, curviplanar fractures, and neoblasts. Approximately 10% of recovered grains displayed granular textures on their exteriors (with neoblasts generally quite equant and <5 µm in size; see examples in Fig. DR1 in the Data Repository), but only zircon 13GGK029-Z25 showed large neoblasts in its interior during CL imaging (Fig. 2B). Consequently, zircon 13GGK029-Z25 was selected for further detailed CL imaging as well EBSD and SIMS U-Pb analysis. It is unknown to what extent mineral separation led to destruction of granular zircon. It is important to note that not all grains in sample 13GGK029 displayed conspicuous shock features, but among the apparently unshocked grains, neither imaging nor a reconnaissance U-Pb age dating survey (>100 grains) identified any that crystallized at ca. 1850 Ma (Sudbury impact). The roof intrusions of the Sudbury melt sheet are very complex heterogeneous rocks (e.g., Anders et al., 2015) containing large proportions of lithic clasts, including many metasandstones. If the roof intrusion did crystallize new, impact-aged zircon, such grains may be a very minor component relative to inherited grains.

Cathodoluminescence imaging of zircon 13GGK029-Z25 revealed three distinct features: the presence of a non-granular region displaying CL-visible banding that may be original to the grain prior to shock metamorphism, many small (<5 µm) granules, and ~20 large (5–100 µm) neoblasts, some of which are clearly euhedral and one of which reaches ~100 µm in dimension (Fig. 2B). Furthermore, CL imaging showed complex internal structures within neoblasts (Figs. 2C–2F). A few neoblasts, ranging from 10 to 30 µm in dimension, appear to display concentric zoning (Figs. 2C and 2D). Another shows sector zoning, with relatively CL-bright regions radiating from the dark center to the corners (Fig. 2F). The absence of baddeleyite (see below) indicates a distinct origin from nucleation of zircon neoblasts around remnant, CL-dark ZrO_2 cores in shocked lunar zircon (Crow et al., 2017). The dark center may, however, represent an inherited zircon core with epitaxial neoblast overgrowth.

EBSD Analysis

EBSD data demonstrate that the large-neoblast-bearing grain 13GGK029-Z25 is composed of zircon, with no evidence for the high-pressure $ZrSiO_4$ polymorph reidite or baddeleyite, ZrO_2 (Fig. DR2). The neoblasts identifiable in CL (Figs. 2B–2F) have crystallographic orientations that are distinct from that of the host zircon (Fig. 2G) but broadly scatter around its orientation (Fig. 3). There is no evidence for the clustering of neoblasts into multiple orientations with distinct disorientation relationships (Fig. 3). In contrast to the host grain, the neoblasts display very low degrees of local misorientation (Fig. 2H), suggesting that they are strain free, similar to large neoblasts in zircon 07VD07-3 from Vredefort (Cavosie et al., 2015). Other shock features in zircon 13GGK029-Z25 include deformation bands parallel to {100} crystallographic planes with misorientations up to ~15° around <001> misorientation axes (Fig. DR3). This is typical of planar

[1]GSA Data Repository item 2017340, full analytical methods, Figure DR1 (additional images of shocked zircon at Sudbury), Figure DR2 (additional EBSD images of zircon 13GGK029-Z25), and Table DR1 (SIMS U-Pb data), is available online at www.geosociety.org/pubs/ft2017.htm or on request from editing@geosociety.org.

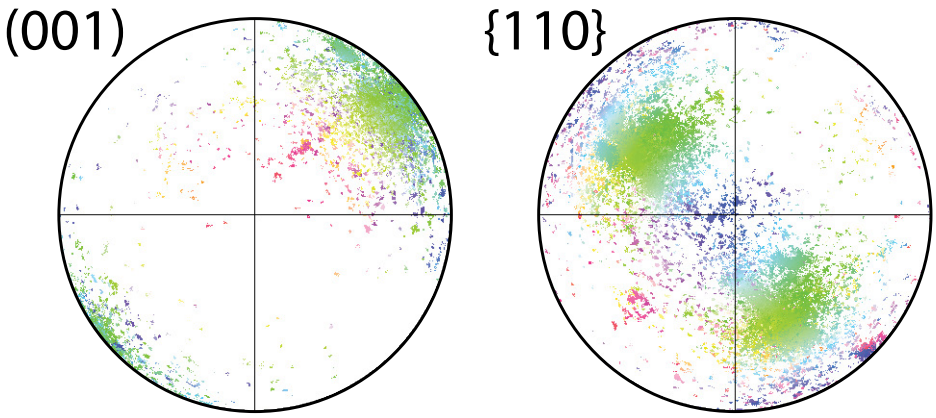

Figure 3. Pole figures showing crystallographic orientation data for shocked zircon 13GGK029-Z25. Each data point is colored using same inverse pole figure scale as used in Figure 2G; therefore the host grain, which is predominantly green in Figure 2G, is represented by cloud of green poles, and individual neoblasts, which have various colors in Figure 2G, are represented by myriad groups of poles scattered around this. There is no evidence for clustering of neoblasts into multiple orientations with distinct disorientation relationships. Plotted with equal area projection, showing only points in negative hemisphere.

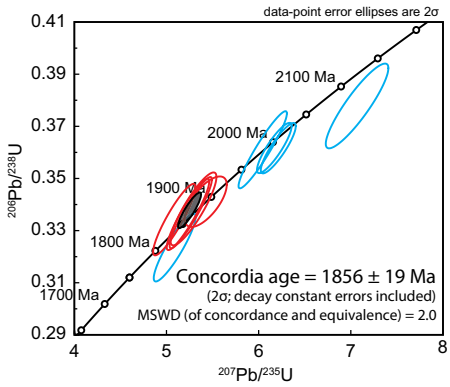

Figure 4. U-Pb concordia diagram for shocked zircon 13GGK029-Z25. Red ellipses represent analyses on neoblasts, and blue ellipses represent analyses on non-neoblastic, variably age-reset areas of host grain (see Fig. 2). Black ellipse is the weighted-mean-error ellipse calculated for the neoblast data shown in red. MSWD—mean square of weighted deviates.

deformations bands (Timms et al., 2012), which are relatively low-temperature and low-pressure shock microstructures (Timms et al., 2017).

SIMS U-Pb Analysis

Ten ion microprobe U-Pb spot analyses were performed on zircon 13GGK029-Z25; five were on low-strain neoblasts, and five were on the host grain (Figs. 2G and 2H). The analyses on the neoblasts give a concordia age of 1856 ± 19 Ma (2σ) with a mean square of weighted deviates (MSWD; combined of concordance and equivalence) of 2.0. This is indistinguishable from high-precision isotope dilution–thermal ionization mass spectrometry (ID-TIMS) ages of zircon from the Sudbury impact melt sheet (1849.53 ± 0.21 Ma and 1849.11 ± 0.19 Ma; 2σ; Davis, 2008). The MSWD of >1 indicates the presence of nonanalytical scatter in the neoblast data. This may be related to a small degree of inheritance in the analysis of the apparently oldest neoblast (this was performed prior to EBSD mapping and appears to have slightly overlapped the host zircon) and possible Pb loss in the apparently youngest neoblast (e.g., Pb loss associated with the ca. 1.65 Ga Mazatzalian-Labradorian orogeny, which affected the Sudbury region, would be expected to slide an error ellipse along concordia). The data indicate that SIMS U-Pb analyses of large neoblasts can routinely give an accurate impact age with a precision of better than 20 m.y. (2σ), which could likely be improved upon with larger spot sizes where possible. The host grain generally displays variable age resetting from a poorly constrained pre-impact age (Fig. 4; Table DR1). Notably, however, one analysis on a non-neoblast domain gives an impact age; this is apparently the result of complete impact-induced Pb loss from a shocked domain in contrast to the new post-impact growth of zircon responsible for the impact age of the neoblasts.

In contrast to our analyses on large neoblasts, a single finely granular zircon from the Onaping Formation at Sudbury, with neoblasts generally ≤1 μm in diameter, was previously found to be ~10% discordant as a result of post-impact Pb loss (Krogh et al., 1996). Our finding that large neoblasts at Sudbury have retained the impact age while small neoblasts at the same crater have compromised ages highlights the utility of the former.

DISCUSSION

The first finding of this study is that large neoblasts (5–100 μm in dimension) are not unique to the Vredefort impact structure and may be a general feature of large impact craters. Regarding their utility for dating impact events, we have also shown that large neoblasts can retain the impact age even under conditions in which smaller, micrometer-scale neoblasts from the same structure have suffered post-impact Pb loss.

Most significantly, this is the first time a crater has been dated using coarsely granular zircon from the upper part of its stratigraphy—previous *in situ* discoveries of such zircon at Vredefort were all in impact-generated mafic melt emplaced beneath the impact melt sheet. The occurrence of coarsely granular shocked zircon in the upper stratigraphy means that the likelihood of them being entrained into a sedimentary system on Earth or a breccia on the Moon is much greater than for grains buried several kilometers below an impact basin.

Regarding the formation of large neoblasts, it is notable that neither reidite nor baddeleyite—which would have indicated high-pressure or high-temperature formation processes, respectively—have been found or preserved in shocked zircon 13GGK029-Z25. Additionally, EBSD analysis provides no evidence for systematic clustering of neoblasts in multiple crystallographic orientations. Systematic clustering of small neoblasts was interpreted as evidence for high-pressure phase transitions at Meteor Crater (Arizona, USA) (Cavosie et al., 2016) and the Acraman impact structure (South Australia) (Timms et al., 2017). Thus our new data suggest that the distinction between small and large neoblasts may not simply be an arbitrary difference in scale. The size of large neoblasts, their internal zonation, and their occurrence in a slowly cooled, fluid-rich environment suggest protracted, post-impact growth in an environment of sustained high temperature. The newly discovered neoblasts grew in shocked zircon that became incorporated into melt bodies in the roof of the melt sheet. These bodies contain lithic fragments, and the rounded shape of many of the studied zircon (Fig. DR1) suggests that they may have derived from metasandstone that was incorporated into the melt body. Critically, the ~2.5-km-thick melt sheet at Sudbury crystallized into a layered intrusion (the Sudbury Igneous Complex). Upon seawater entering the crater, fuel-coolant interactions formed the lower breccias of the Onaping Formation, and sustained volcanism (e.g., Ubide et al., 2017) and hydrothermal activity (e.g., Ames et al., 1998) provide evidence for protracted cooling of the environment in which the large neoblasts formed. Moser et al. (2011, p. 133) suggested that a similar process may have acted in the base of the Vredefort crater, where "the coarse polycrystalline texture of the xenocrysts may be caused by prolonged exposure to superheated impact melt and elevated regional post-impact temperatures."

Increased knowledge of how and where large neoblasts form has implications for the interpretation of *ex situ* grains with similar textures.

Crow et al. (2017) reported coarsely granular lunar zircon apparently displaying granoblastic textures similar to those of some grains from Vredefort (e.g., Cavosie et al., 2015) but unlike the euhedral forms documented here. Additionally, the lunar neoblasts commonly have baddeleyite cores, suggesting that ultrahigh temperature dissociation of zircon preceded neoblast growth (Timms et al., 2017). Regardless of these differences, the large size of the lunar neoblasts (>20 μm) suggests that, similarly to large terrestrial neoblasts, they are likely to have formed as a result of protracted elevated temperatures after initial shock metamorphism. This could have occurred because the shocked grains were incorporated into melt bodies either at the base or above the roof of the actual melt sheet. Crow et al. (2017) noted that their ca. 4.2 Ga age for a neoblastic Apollo 14 lunar zircon is coincident with the basin-forming event proposed by Norman and Nemchin (2014), and that their ca. 4.33 Ga age for neoblasts in two Apollo 15 grains coincides with a major peak in lunar zircon ages. We suggest that the 4.33 Ga impact recognized by Crow et al. (2017) may have been a basin-forming event that sustained the high temperatures apparently required for large neoblast growth. Insight from *in situ* neoblasts may eventually help to link *ex situ* granular zircon grains in lunar breccias with specific impact structures, which would improve calibration of the lunar cratering record—and thus inner solar system impact flux—with radiometric ages.

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