GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

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https://doi.org/10.1130/focus082019.1

Untying microscopic Gordian knots: The granular (zircon) details of impact basins

Aaron J. Cavosie
Space Science and Technology Centre, School of Earth and Planetary Science, Curtin University, Perth, Western Australia 6102, Australia

One of the challenges in studying the formation of giant meteorite impact basins, which are massive structures with diameters up to thousands of kilometers that profoundly affect the crust and mantle of planets, is the nature of available data. Scientists are tasked with reconciling geological evidence with remotely sensed data to validate models. In the case of the Moon, a smorgasbord of impact basins is left over from early meteorite bombardment, but they are not easy to sample. Reconstructing Orientale, a >900 km lunar multi-ring basin, was made possible in the absence of geological samples by using high-resolution orbital observations from NASA's Gravity Recovery and Interior Laboratory (GRAIL) spacecraft and numerical modeling (Johnson et al., 2016). Closer to home, the situation is different. Many large impacts must have formed on Earth (e.g., Marchi et al., 2014); however, only three confirmed terrestrial structures are large enough to be considered impact basins (Grieve and Therriault, 2000). Uncertainty remains about the nature of these basins due to their age, state of preservation, and accessibility. Chicxulub (Mexico) is the youngest and best-preserved terrestrial impact basin, at ~180 km and 65.5 Ma, yet it is buried by platform sediments in the Gulf of Mexico; international drilling recently targeted the peak ring to test hypotheses on how granitoid bedrock is uplifted from depth to the near surface in minutes (Riller et al., 2018). The Sudbury (Canada) and Vredefort (South Africa) structures are even larger, with apparent diameters from 200 to 300 km, but both formed in the Paleoproterozoic; unraveling their histories is complicated, as they have been deformed (Sudbury) or are deeply eroded (Vredefort). The Vredefort impact structure is widely agreed to be Earth's largest impact basin, with estimates of up to 300 km in diameter (Therriault et al., 1997), and it is currently Earth's oldest precisely dated structure at 2.02 Ga (Kamo et al., 1996; Moser, 1997). However, the upper 8–11 km of the structure have been removed by erosion (Gibson et al., 1998), including a 400–800-m-thick impact melt sheet (Ivanov, 2005). Exposed rocks, representing the floor of the basin, record shock pressures broadly up to ~20 GPa (Gibson and Reimold, 2008).

Among exposed basement rocks is the Vredefort granophyre, an unusual melt rock that occurs as a series of vertical dikes (Therriault et al., 1996). Meteoritic Os uniquely identifies it as a product of impact melting (Koeberl et al., 1996); however, the origin of the granophyre is controversial in the context of the formation of the Vredefort structure. The occurrence of supracrustal rock clasts as inclusions in the granophyre has been cited as evidence that the melt formed at or near the surface and was injected downward, up to ~10 km, into the lower levels of the impact basin (e.g., Buchanan and Reimold, 2002). If correct, constraining the origin of the granophyre plays a key role in understanding the interplay between melt and deep crustal fractures during the formation of large impact basins.

In this issue of *Geology*, Kovaleva et al. (2019, p. 691) address the 'deep injection' model for the granophyre, and describe an occurrence of a type of granular zircon not previously reported from the Vredefort structure. Remarkably, the grains are found within a clast of shock-metamorphosed granite that is cross-cut by a centimeter-scale pseudotachylite vein, and the entire granite clast is entrained in a granophyre dike (see Kovaleva et al.'s figure 2A). The significance is that the granular zircon preserves evidence for the former presence of reidite, a high-pressure $ZrSiO_4$ polymorph. Such granular grains are known as FRIGN zircon ('Former Reidite in Granular Neoblastic' zircon; Cavosie et al., 2018), which represents the final state of a reidite-bearing shocked zircon that gets heated beyond the thermal stability of reidite, resulting in reversion of reidite to zircon neoblasts with systematic orientation relations (Timms et al., 2017). Identification of granular grains as FRIGN zircon requires crystallographic orientation analysis; until now, all known occurrences were restricted to impact glass and partially devitrified impact melt rock (e.g., Cavosie and Koeberl, 2019). FRIGN zircon has also been shown to reliably record impact age (Kenny et al., 2019), and is thus a useful U-Pb geochronometer. Reidite requires formation conditions of >30 GPa in crystalline rocks and has not previously been reported from Vredefort (Leroux et al., 1999). It is the evidence of former reidite, and the geological context of the shocked granite clast within the Vredefort granophyre, that provides new, mineral-based confirmation for one of the more unusual features of the giant Vredefort impact structure.

To further explore the significance of these results, it is useful to note that while shocked zircon was first described from Sudbury (Krogh et al., 1984), Vredefort has emerged as the de facto 'type locality' for shocked zircon, given the sheer number of published studies. Much of what is known about how zircon responds to progressive shock deformation has arisen from empirical studies of Vredefort crystalline rocks (e.g., Kamo et al., 1996; Moser et al., 2011) and Vredefort detrital grains in fluvial systems (e.g., Cavosie et al., 2010; Erickson et al., 2013; Montalvo et al., 2017). Despite an extensive body of work, reidite has not previously been reported, which likely reflects the observation that it is generally restricted to the uppermost regions of impact settings, in rocks that record high shock pressures, such as impact melt, breccia, ejecta, and, less commonly, bedrock; these upper crater environments have all been eroded from the Vredefort structure.

New insights from the work of Kovaleva et al. include identification at Vredefort of mineral evidence for pressures of at least 30 GPa, which is among the highest yet reported. The pressure constraints reported by Kovaleva et al. reinforce prior estimates of up to 30 GPa, based on mineral reactions in other clasts from the Vredefort granophyre (Buchanan and Reimold, 2002); in this case, nailing down evidence of a high-pressure phase is more definitive. More broadly, the presence of a granite clast with zircon grains that

CITATION: Cavosie, A.J., 2019, Untying microscopic Gordian knots: The granular (zircon) details of impact basins: Geology, v. 47, p. 799–800, https://doi.org/10.1130/focus082019.1.

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previously hosted reidite lends further support to interpretations for a near-surface origin of the granophyre melt. In this scenario, the granophyre dikes are deep apophyses of a large impact melt sheet that were injected down into basement rocks (as has been proposed previously) and incorporated the granite clast en route (e.g., French and Nielsen, 1990; Therriault et al., 1996). Preservation of reidite in intact granitoid is rare (Cox et al., 2018); Kovaleva et al. infer that granite bedrock was near the surface at the time of impact, at least locally, until disrupted by granophyre melt. Finally, the serendipitous presence of a pseudotachylite vein in the FRIGN zircon–bearing granite clast indicates that pseudotachylites also formed in the near-surface environment, prior to entrainment and transportation of the granite clast to deeper levels of the structure in the Vredefort granophyre.

It is remarkable that an ~5 cm lithic clast can contain such a wealth of information (granular zircon; former reidite; shocked granitoid; pseudotachylite vein; granophyre association), and confirms the great length-scales of downward material transport and mobility of impact melt, as well as provides glimpses of the long-eroded near-surface environment of a large impact basin. With thousands of lithic clasts and xenocrysts in the Vredefort granophyre, there are undoubtedly other discoveries lying in wait that will further contribute to recreating the Vredefort event and paleoenvironment. Complicated zircon grains have long been recognized in impact settings (El Goresy, 1965); however, granular zircon is seemingly ubiquitous in impact environments on Earth (e.g., Cavosie et al., 2015) and the Moon (e.g., Crow et al., 2017). In one sense, granular zircon formed by reversion of reidite is something of a microscopic Gordian knot; one that can now be untied with orientation analysis to reveal otherwise obscured high-pressure histories. Understanding how it forms, and where it can be found, provides new tools that assist in recreating cosmic cataclysms on Earth and at other locations nearby.

ACKNOWLEDGMENTS

I am indebted to many colleagues for lively discussions about shock deformation of zircon and other minerals. Any misguided mythological musings can be attributed to me.

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