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

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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 multiring 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). Metarotic 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 supra-crustal 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 ZrSiO₄ 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 (Kenyon 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


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