Reconciling early impacts and the rise of life

Aaron J. Cavosie
Department of Geology, University of Puerto Rico, P.O. Box 9000, Mayagüez, Puerto Rico 00681, USA

When did life first appear? This question has profound implications for understanding under what conditions life originated and then colonized Earth. Determining how fast life can appear on young, dynamically evolving planets such as early Earth assists astrobiologists searching for life on exoplanets (distant worlds outside of our solar system), 1700 of which have been confirmed to exist (Rowe et al., 2014). Searching for life’s origin is difficult, because the tapestry of its remains in the geological record gets thinner as one looks further back in time. Silicified carbonates in Western Australia provide evidence for stromatolite communities by ca. 3.43 Ga (Allwood et al., 2006). Tantalizing clues of older life, low carbon isotope ratios interpreted to have a biological origin, have been documented in ca. 3.8 Ga metasedimentary rocks in southwestern Greenland (Schidlowski, 1988; Rosing, 1999). Evidence for habitats which could support life extends even further back: “supracrustal” oxygen isotope ratios in detrital Hadean zircons require low-temperature aqueous alteration of igneous protoliths by 4.3 Ga (Valley et al., 2002; Cavosie et al., 2005). With liquid water and cool surface conditions, life could thus have arisen anytime between 4.3 Ga and 3.8 Ga, but the inner solar system was subject to impact bombardment at this time. The Moon experienced increased impact flux from 4.2 Ga to 3.85 Ga, culminating in a Late Heavy Bombardment (Tera et al., 1974; Kring and Cohen, 2002; Norman and Nemchin, 2014). Earth probably suffered the same bombardment, but no evidence has been found thus far in the geological record. Understanding the evolution of the Earth during this critical time requires reconciliation of the impact history and the rise of life.

In this issue of Geology, two studies report key information about Earth’s largest and oldest known impact, the 2.02 Ga Vredefort Dome in South Africa. In the first study, Cupelli et al. (2014, p. 403) present zircon data which the authors interpret as evidence of preserved remnants of the Vredefort impact melt sheet. Such sheets, igneous rocks formed by impact-generated melting, are known from impact structures such as Sudbury (Ontario, Canada; Therriault et al., 2002), but not unequivocally from the Vredefort Dome. Numerical modeling predicts that a several-km-thick melt sheet formed during that impact (Ivanov, 2005), but it was assumed to have been removed during erosion of the structure (Gibson and Reimold, 2008). Cupelli et al. identify foliated gabbro-norite, exposed as a bifurcating mafic dike network within granitoid bedrock in the central uplift of the Vredefort Dome, as vestiges of a melt sheet. Unshocked impact-age zircons in the gabbro-norite have been used as evidence for a syn-impact igneous origin (Moser, 1997), but the foliation and zircons could have formed during impact-induced metamorphism (Gibson and Reimold, 2008). Cupelli et al. document a population of unshocked impact-age zircons in the gabbro-norite, and use cathodoluminescence imaging to show that these zircons preserve oscillatory growth zoning, a hallmark of igneous origin. The same zircons yield Ti-in-zircon crystallization temperatures from 795 °C to 928 °C, uncommonly high for zircons in most crustal rocks (Fu et al., 2008), but overlapping with Sudbury melt sheet zircons (Darling et al., 2009; Wielicki et al., 2012). Subchondritic εNd values in the zircons reflect variable degrees of crustal assimilation, as might occur when the melt sheet incorporates crustal rocks in the complex environment of the newly formed crater. Cupelli et al. interpret the foliation as flow banding from downward injection of the mafic melt during post-impact crater modification. Extending their results to an earlier Earth, Cupelli et al. highlight that rocks with petrofacies similar to the Vredefort gabbro-norite occur widely across Archean cratons, and speculate that similarly deformed impact melts may have been overlooked in the absence of macroscopic evidence of shock deformation (e.g., shatter cones). Revisiting zircon collections from suspect rocks in Archean terrains to interrogate U-Pb ages, Ti abundance, and εNd composition holds promise for discovering ancient impact melts.

Huber et al. (2014, p. 375 in this issue) report spherule-bearing sedimentary rocks from Karelia (Russia), interpreted to represent distal ejecta from the Vredefort impact. Two cores acquired during the FARDEEP (Fennoscandian Arctic Russia—Drilling Early Earth Project) drilling program of the Paleoproterozoic Ziaonega Formation in Fennoscandia encountered what the authors interpret as altered impact spherules, droplets of melt and vapor formed in the atmosphere during crater excavation. The deposition age of spherule layers generally cannot be determined directly, but deposition is constrained to between 2.05 Ga (based on Re-Os in organic matter) and 1.98 ± 0.057 Ga (based on the Pb-Pb age of a mafic sill), a time frame consistent with an origin from the 2.02 Ga Vredefort impact. Huber et al. report spherical- and dumbbell-shaped spherules wholly altered to secondary phases (calcite, biotite, pyrite), as typical for most Precambrian spherules (Glass and Simonson, 2012). X-ray fluorescence, electron microscopy, and inductively coupled plasma–mass spectrometry (ICP-MS) are used to document an impact origin. Ir abundances (<1 ppb) are generally low, but Ru/Ir, which averages 2 in the spherule layers and is assumed to not fractionate during weathering, is similar to that in chondritic meteorites (Ru/Ir = 1.5), and much lower than in continental crust (Ru/Ir = 10). Ejecta as old as 3.47 Ga have been described (Byerly et al., 2002), but source craters are unknown. If the Karelian spherules are Vredefort-derived, they are the oldest ejecta with a known source crater, at ~150 m.y. older than Sudbury ejecta (Addisson et al., 2005). Spherule sizes described by Huber et al. (~800 µm) require the crater to have been <2500 km away, allowing constraints on the distance between Fennoscandia and the Kaapvaal craton at the time of impact.

Shocked minerals provide diagnostic evidence of impact (French and Koebel, 2010), but are rare or absent in Precambrian impact melt sheets and ejecta from Vredefort and elsewhere. Widespread in target rocks, shocked minerals survive erosion and sedimentary transport, and constitute single-mineral records of eroded impact structures. Common minerals in siliclastic rocks (including zircon, quartz, monazite, and apatite) occur as detrital shocked grains in modern sediments eroded from bedrock at Vredefort, Sudbury, and other structures, up to 2 b.y. after the impact (Cavosie et al., 2010; Erickson et al., 2013; Cavosie and Lugo, 2014; Thomson et al., 2014). Detrital shocked zircons (Fig. 1) offer enormous potential for determining the timing of early impacts, as shock microstructures are resistant to annealing, and Hadean detrital zircons with ages up to 4.4 Ga are known (Valley et al., 2014). Such zircons would presumably have been shocked if the Late Heavy Bombardment was global; the erosional records of Vredefort and Sudbury show that such grains could reside in younger sedimentary rocks.

Given the low likelihood of discovering an intact impact structure from early Earth, these approaches provide new ways to search for impact-evidence during the critical period, 4.3 Ga to 3.8 Ga. Discovery of such ancient impact records may provide constraints on when Earth’s first inhabitants arrived.
produce diffraction patterns due to the loss of crystallinity. Black semi-concentric regions within the zircon are zones of radiation damage, which do not produce diffraction patterns due to the loss of crystallinity (from Thomson et al., 2014).

REFERENCES CITED


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