**THE RESPONSE OF ZIRCON TO EXTREME PRESSURES AND TEMPERATURES – INSIGHTS FROM A LIGHTNING STRIKE AND A NUCLEAR EXPLOSION.**

G. G. Kenny[1]*, M. A. Pasek[2], J. J. Bellucci[1]
[1]Department of Geosciences, Swedish Museum of Natural History, SE-104 05 Stockholm, Sweden, [2]School of Geosciences, University of South Florida, Tampa, FL 33620, USA. *gkennyeire@gmail.com

**Introduction:** Hypervelocity impacts induce extreme pressures and temperatures that are not normally produced by endogenic geological processes. Features created in response to these conditions can thus be used to infer the occurrence of a bolide impact and confirm a suspected impact structure (planar deformation features, PDFs, in quartz are perhaps the best known of these; e.g. ref. [1]). The mineral zircon ($ZrSiO_4$) responds to extreme pressure–temperature (P–T) conditions in a variety of crystallographically controlled ways (e.g., ref. [2]). Given the increasing use of zircon in studies of shock metamorphism and impact cratering, there is an imperative to understand which features in zircon are unique to hypervelocity impacts and which may form as a result of other extreme P–T excursions, such as lightning strikes and nuclear explosions. Additionally, analysis of deformation and phase transitions in zircon may shed light on the P–T conditions of lightning strikes and prove useful in nuclear forensic investigations.

Previous studies of fulgurites (tubular bodies of glass and fused clasts that formed in response to lightning) have noted zircon with rims of $ZrO_2$ [3,4] and one study documented a Zr-rich patch of glass that was interpreted to represent a zircon grain that had been entirely melted [4]. Zircon grains with rims of vermicular $ZrO_2$ have also been documented in trinitite (glass formed in response to the first nuclear explosion, in New Mexico, USA, in July 1945) [5].

With the aim to recognize features that form in response to extreme P–T excursions but are not unique to hypervelocity impacts, and to understand better the P–T conditions of these events, we undertook imaging and microstructural analysis of zircon and baddeleyite (i.e., monoclinic $ZrO_2$) in a fulgurite and in trinitite.

**Samples:** The fulgurite sample studied here formed as lightning struck vegetated soil in York County, Pennsylvania, USA, in 2004. The tube has a diameter of ~2 cm and a central void of ~0.5 cm. The sample of trinitite studied here was previously reported on by [6].

**Methods:** The fulgurite and trinitite were mounted in epoxy and cut to expose their interiors, which were polished with diamond suspension and colloidal silica. Imaging and microstructural characterization of zircon and baddeleyite by electron backscatter diffraction (EBSD) analysis were performed on an FEI Quanta FEG 650 scanning electron microscope (SEM) at the Swedish Museum of Natural History, Stockholm.

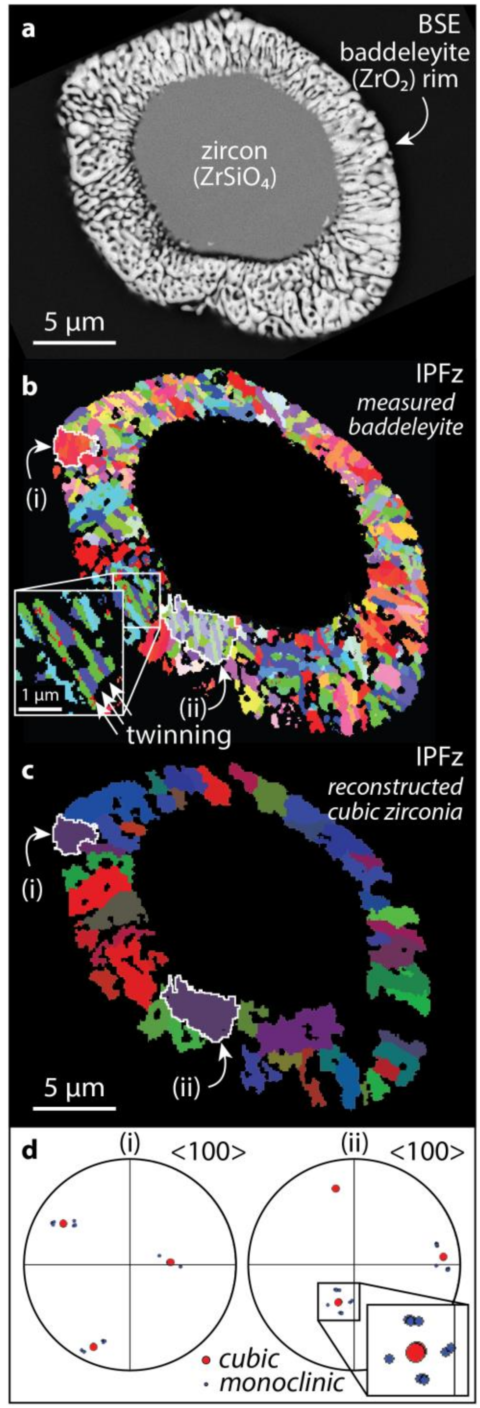


**Fig. 1.** Imaging and microstructural characterization of a zircon grain with a baddeleyite rim from a fulgurite (lightning-produced glass). BSE – backscattered electrons. IPF – Inverse Pole Figure.

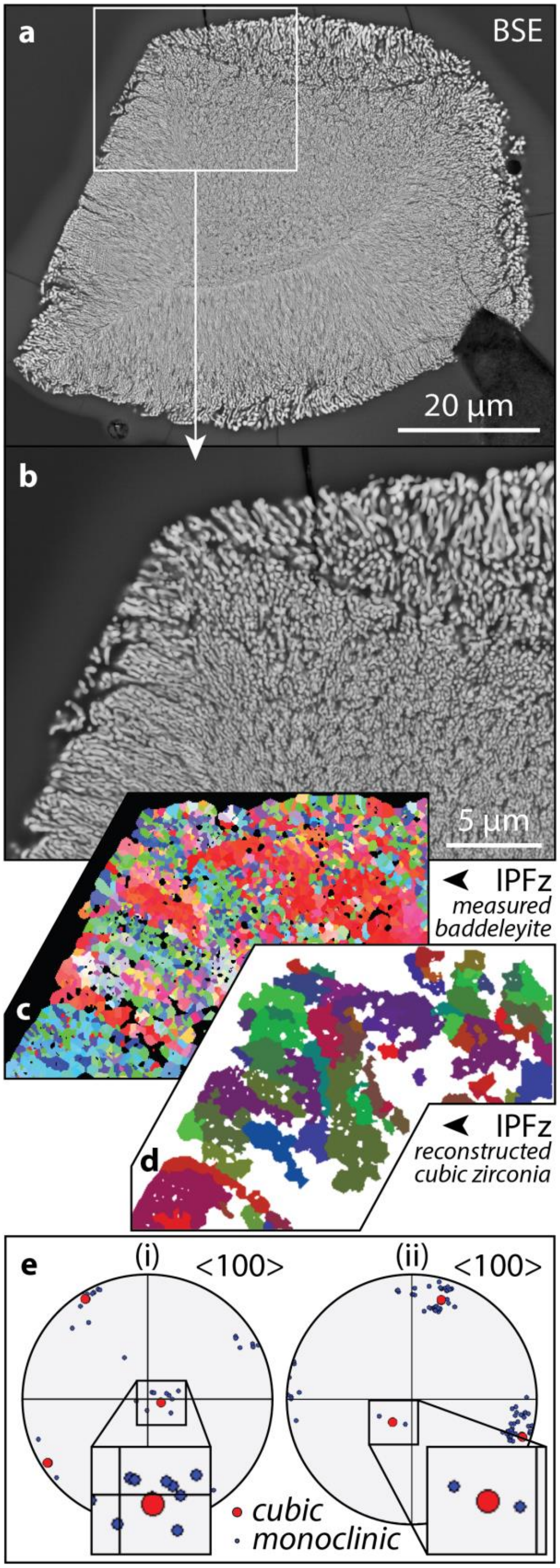


**Fig. 2.** Imaging and microstructural characterization of vermicular baddeleyite from trinitite, glass produced by the first nuclear blast. BSE – backscattered electrons. IPF – Inverse Pole Figure.

Microstructural data were processed in Oxford Instruments Channel 5 software. Data cleaning comprised a wildspike correction and a nearest-neighbor zero-solution extrapolation. Analysis of neighbor-pair disorientation relationships was done in the ARPGE software [7].

**Results:** Ninety-one Zr-rich grains (86 zircon grains and five grains composed entirely of vermicular baddeleyite) were identified in the fulgurite and one Zr-rich grain (entirely vermicular baddeleyite) was identified in the sample of trinitite. Comprehensive results for the fulgurite sample are presented in ref. [8].

Microstructural analysis of (i) a rim of vermicular $ZrO_2$ on a zircon grain in the fulgurite (Fig. 1a), and (ii) the grain entirely composed of vermicular $ZrO_2$ in the trinitite (Fig. 2a-b) reveals that both are composed of clusters of grains of monoclinic $ZrO_2$ (Figs. 1b, 2c). The clusters, up to 5 µm in diameter, preserve up to twelve (but usually less) unique but systematically related crystallographic orientation variants (e.g., Figs. 1c-d, 2d-e). This is consistent with cubic to monoclinic transformation and evidences the former presence of cubic $ZrO_2$ in this rim now composed solely of monoclinic $ZrO_2$ [9]. Cubic $ZrO_2$ is a high-temperature phase (forming at T>2370°C at low pressure) and previously documented natural occurrences were associated with hypervelocity impacts [10,11].

**Implications:** Evidence for precursor cubic $ZrO_2$, despite indicating extreme pressure–temperature conditions, is not unique to hypervelocity impacts but may be related to lightning [8] and even nuclear blasts. Consequently, this phase cannot be considered diagnostic of hypervelocity impact.

**Acknowledgments:** This project received funding from the European Union's Horizon 2020 research and innovation program under the Marie Skłodowska-Curie Individual Fellowship Grant Agreement No. 792030, supporting G.G.K. We thank Cyril Cayron for helpful discussions and support with ARPGE software.

**References:** [1] French, B. M. & Koeberl, C. (2010) *Earth-Sci. Rev.*, *98*, 123–170. [2] Timms, N. E. et al. (2017) *Earth-Sci. Rev.*, *165*, 185–202. [3] Essene, E. J. & Fisher, D. C. (1986) *Science*, *234*, 189–193. [4] Pasek, M. A. et al. (2012) *Contrib. Mineral. Petrol.*, *164*, 477–492. [5] Lussier, A. J. et al. (2017) *Am. Mineral.*, *102*, 445–460. [6] Bellucci, J. J. et al. (2017) *Anal. Chem.*, *89*, 1887–1891. [7] Cayron C. et al. (2007) *J. Appl. Crystallogr.*, *40*, 1183–1188. [8] Kenny, G. G. & Pasek, M. A. (2021) *Sci. Rep.*, doi.org/10.1038/s41598-021-81043-8 [9] Cayron, C. et al. (2010) *J. Am. Ceram. Soc.*, *93*, 2541–2544. [10] Timms, N. E. et al. (2017) *Earth Planet. Sci. Lett.*, *477*, 52–58. [11] White, L. F. et al. (2020) *Nat. Astron.*, *4*, 974–978.