A Ti-, Zr-, Th- and U-RICH HYDROTHERMAL ASSEMBLAGE ASSOCIATED WITH THE PRECAMBRIAN YARRABUBBA IMPACT STRUCTURE (WESTERN AUSTRALIA).

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Introduction: The deeply eroded Yarrabubba impact structure in the Archean (~3.0–2.65 Ga) granite-greenstone terrain of the north-central Yilgarn Craton of Western Australia is among the oldest impact structures on Earth. Impact lithologies include the 'Barlangi Granophyre' (BG) interpreted as an injection of impact melt into the crater basement (i.e., an impact melt rock that locally contains granitic xenoliths); fault-related pseudotachylites; monomict granite-derived lithic breccias; and shatter-coned granite that also contains shocked quartz [1,2]. The BG is well exposed at 'Barlangi Rock', a monolith accessible from the Meekatharra–Sandstone Road (27°11'S, 118°50'E).

The original size of the Yarrabubba impact structure is poorly constrained [1]. Extrapolation of a ~25 km-diameter magnetic anomaly that coincides with the impact structure suggests an original diameter of ~30–70 km [2]. Likewise, the age of the Yarrabubba impact is only loosely bracketed by the age of the youngest shocked target rock, the ~2.65 Ga Archean 'Yarrabubba Granite'; dolerite dikes possibly as young as ~1.2 Ga [3], which seem to postdate the impact structure [1,2]; and a Mesoproterozoic alteration (minimum) ^{40}Ar/^{39}Ar age of ~1.1 Ga for pseudotachylites [4]. Uranium-lead geochronology of zircon grains recovered from the BG predominantly yielded ages between 2.79 Ga and 2.65 Ga [5,6].

Post-impact K-metasomatic and hydrothermal alteration of the Yarrabubba impactites produced veins of bladed calcite locally replaced by silica, K-feldspar veins, veinlets of fluorite, biotite, chlorite, prehnite, and caused micaceous overprint of the shocked target granite [2,7]. The present study focuses on newly discovered late-stage zircon and aggregates of zircon intergrown with thorite (henceforth thorite–zircon) found in the BG alongside secondary TiO_2.

Analytical Methods: Scanning electron microscopic (SEM) analysis of zircon and thorite–zircon in a polished thin section of the BG was carried out using a VEGA3 TESCAN instrument equipped with a high count-rate X-MAX 50 silicon drift detector for energy dispersive spectrometery (EDS) analysis and a panchromatic cathodoluminescence (CL) detector at the Centre for Microscopy, Characterisation and Analysis at the University of Western Australia.

New Observations: In contrast to an earlier report of zircon crystals with igneous-type oscillatory zoning in the BG [5], this SEM study revealed the presence of irregular-shaped zircon aggregates ≤100 µm in size that are commonly skeletal-microporous (Fig. 1A, B), locally microcrystalline, veinlet- and stringer-like (Fig. 1C), and also occur as micro-'droplets' (Fig. 1D). Zircon in these aggregates is commonly intergrown with thorite-zircon, Fe–Ti-oxides (Fig. 1A, B), and TiO_2 (likely rutile). These zircon/thorite-zircon aggregates preferentially grew in voids within the BG, and are in places associated with open fractures in chlorite alteration domains that are filled with zircon and thorite-zircon (Fig. 1D). Individual zircon crystals in the aggregates are typically subhedral (Fig. 1A). Imaging of the irregular-shaped zircon aggregates using SEM-CL shows no obvious internal zoning, and EDS analysis revealed that the zircon contains up to ~5 wt% Fe_2O_3, ~4 wt% Al_2O_3, ~3 wt% CaO, and ~4 wt% UO_2. Thorite–zircon has up to ~45 wt% ThO_2. Similar to zircon, microporous TiO_2 containing up to ~1 wt% of Nb_2O_3 preferentially crystallized in void spaces within the BG.

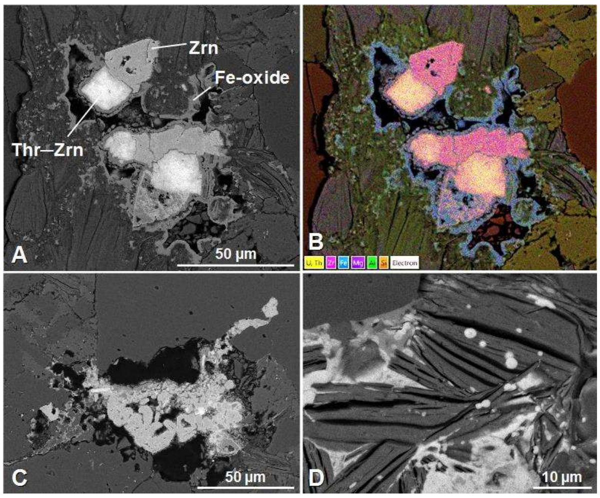

Fig.1: Hydrothermal zircon and thorite–zircon aggregates in the Barlangi Granophyre. **A**: Backscattered electron image showing zircon (Zrn)/thorite–zircon (Thr–Zrn) aggregate and Fe-oxide rim; **B**: X-ray element map of scene shown in A (same scale); pink: Zr; yellow: U and Th; blue: Fe. **C**: Aggregate of zircon (light gray) and thorite–zircon (white) microcrystals grown in a cavity; a zircon 'stringer' extends into open fractures in quartz; **D**: Secondary zircon micromasses and -'droplets' (bright) associated with chlorite.

Discussion: In terms of their microtexture and high concentrations of Fe, Al, and Ca, the irregular-shaped zircon aggregates in the BG are similar to hydrothermal zircon found in endogenic geologic settings (e.g., [8–11]). Substantial amounts of U and Th in the BG zircon and thorite–zircon suggests these aggregates may have formed nucleating around pre-existing igneous (possibly radiation-damaged [12,13]) zircon and thorite grains overprinted by the impact. Igneous-type zircon crystals previously reported from the BG only contain ≤538 ppm U and ≤335 ppm Th [5]. The newly crystallized zircon/thorite-zircon aggregates, significantly richer in U and Th, probably formed at the expense of those proto-crystals, possibly via a dissolution and reprecipitation process [13].

The timing of hydrothermal zircon, thorite–zircon, and TiO_2 formation is poorly constrained, but from textural relationships must have occurred after the crystallization of the BG. This constrains the maximum age of hydrothermal crystallization to ~2.79–2.59 Ga [5,6] or later. A Mesoproterozoic alteration event indicated by a series of U–Pb [3] and $^{40}Ar/^{39}Ar$ [4] ages around ~1.2–1.1 Ga seems to mark the younger age limit for hydrothermal alteration at Yarrabubba. Absent any precise and accurate ages for the Yarrabubba impact and hydrothermal alteration in the BG, it remains speculative whether the zircon, thorite–zircon, and TiO_2 were formed in direct response to the Yarrabubba impact or in a later, endogenic, hydrothermal event unrelated to impact. The youngest metal-ore mineralization in the Yilgarn Craton generally dates back to the Archean (~2.66–2.63 Ga) [14–15], with some magmatic-metasomatic events in the Proterozoic (~2.3–2.1 Ga) [16]. However, the northern margin of the Yilgarn Craton has a protracted tectonic history throughout the Paleo- to Mesoproterozoic (~2.0–1.2 Ga) caused by convergence with the Pilbara Craton, formation of the West Australian Craton, and subsequent reworking [17]. Because Zr is rather immobile in low-temperature fluid systems and as zircon is usually a stable mineral phase [18], hydrothermal alteration of the BG likely occurred at elevated temperatures (>250°C [9,17]), and presumably under the presence of alkaline aqueous fluids [7] that promote Zr mobility [18]. Post-impact hydrothermal activity, likely driven by the heat from the cooling Yarrabubba impact crater [7], may have provided the right conditions for Zr (as well as Th and Ti) to be remobilized in the BG impact melt body.

Although impact melt lithologies with granophyric texture are known from other large impact structures on Earth, such as Vredefort (South Africa, e.g., [19]) and Sudbury (Canada, e.g., [20]), no hydrothermal zircon and thorite–zircon similar to that in the BG has so far been described from terrestrial impactites. However, U- and Th-rich hydrothermal assemblages inside impact craters are not restricted to Yarrabubba. An impact-induced hydrothermal system, linked to the formation of U- and Th-rich bitumen nodules in impact breccias, was reported from the marine Lockne impact structure in Sweden [21]. The Vredefort, Carswell (Canada), and Terny (Ukraine) impact structures host pro- and syngenetic uranium deposits [22], which may have – at least locally – facilitated the circulation of U-rich fluids in response to impact.

Impact crater-hosted hydrothermal systems are thought to have served as important niches for microbial life [23–25]. The Precambrian Yarrabubba impact occurred at a time when planet Earth was exclusively inhabited by microbial life forms. As radioactive radiation has been shown to cause mutagenic effects in microbes (e.g., [26]) and can promote the concentration of carbon [21], one can speculate whether U- and Th-rich domains in hydrothermal systems such as the one hosted by the Yarrabubba impact structure may have been natural laboratories for cell mutation and adaptation in the evolution of early terrestrial microbial life. Thus, a locally U-Th-rich hydrothermal system in response to the Yarrabubba impact might be of particular interest with respect to the development and evolution of life on the early Earth (and possibly Mars).

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