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Ultrafast Ultrahigh-Temperature Pulses in the Early Precambrian Revealed by NanoSIMS-Guided Zircon Diffusion Chronometry

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Resolving the tempo of extreme metamorphism in the early Earth remains a central challenge in Precambrian geodynamics. Conventional geochronology lacks the temporal resolution to detect sub–million-year thermal events, limiting our ability to evaluate whether modern-style, short-lived tectonothermal pulses operated in early orogens. Here we integrate phase equilibria modeling, thermobarometry, high-resolution NanoSIMS trace-element mapping, and diffusion modeling in zircon from Paleoproterozoic ultrahigh-temperature (UHT) pelitic granulites of the Jiao-Liao-Ji orogen, North China craton.

Petrological constraints define a clockwise P–T evolution from ~1.3 GPa/850 °C to peak conditions ≥940 °C at ~0.6–0.7 GPa, followed by cooling to ~600 °C. Zircons preserve Neoarchean detrital cores overgrown by ca. 1.85 Ga metamorphic rims. Oscillatory Ti–Dy–Yb zoning within detrital cores, resolved at 100 nm scale by NanoSIMS, provides a natural diffusion archive of the metamorphic event. Forward modeling of lamella-scale compositional relaxation yields heating durations of 0.02–0.6 Myr and UHT residence times of 0.05–1.3 Myr, documenting ultrafast (~0.1 Myr) UHT pulses embedded within a prolonged Paleoproterozoic orogen.

These results demonstrate that extreme crustal temperatures in the early Precambrian were not necessarily sustained over long durations, but instead occurred as transient thermal spikes comparable to those recognized in Phanerozoic belts. Spatial and temporal links to coeval mafic intrusions support episodic mantle upwelling as the heat source, consistent with vigorous crust–mantle interaction during supercontinent assembly.

Importantly, this study provides the first empirical constraints on Ti diffusivity in natural zircon at crustal temperatures, revealing rates several orders of magnitude faster than experimental extrapolations. This finding significantly refines the reliability of Ti-in-zircon thermometry and establishes zircon diffusion chronometry as a robust, sub–million-year geospeedometer for early Earth processes.

Our results highlight diffusion chronometry as a transformative tool for quantifying the rates of high-temperature metamorphism in Archean–Paleoproterozoic terranes, offering new constraints on the dynamics and thermal regimes of early plate tectonics.