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Quantifying Proterozoic deep-crustal cooling and exhumation timescales using garnet–cordierite diffusion chronometry

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Deep-crustal granulite-facies rocks provide a unique archive of lower-crustal thermo-tectonic evolution. They offer a means to distinguish between short-lived vs. long-lived high-temperature residence, a distinction that remains fundamental to understanding orogenic processes on the Precambrian Earth. Here, we apply diffusion chronometry of Fe–Mg exchange across garnet–cordierite and garnet–biotite interfaces to quantify cooling and exhumation rates in deep crustal, migmatitic gneisses and amphibolites. The studied rocks derive from a Proterozoic lower-crustal block of the northeastern Indian Shield (Assam–Meghalaya Gneissic Complex) that experienced high-grade metamorphism at ca. 1.6 Ga. Integrated petrography, phase-equilibrium modelling, and zircon–monazite U–Pb geochronology constrain peak conditions of ~725–755 °C at ~6 kbar along a clockwise P–T path, with peak metamorphism and partial melting at ca. 1.6 Ga. Major-element profiles across garnet rims record diffusional re-equilibration of Fe–Mg during cooling, whereas preservation of prograde Ca zoning reflects its comparatively slow diffusion, allowing prograde growth to be distinguished from retrograde modification. Forward diffusion modelling of garnet–cordierite interfaces reveal non-linear cooling, with relatively rapid cooling at high temperatures (> 700 °C; 5 °C/Ma) followed by progressively slower cooling at lower temperatures (2.2 °C/Ma). When integrated with the P–T path, these rates correspond to exhumation rates of ~0.1–0.6 mm/yr, implying prolonged residence at lower-crustal depths. This cooling–exhumation style is consistent with limited tectonic exhumation and dominantly erosional unroofing. Our results highlight the potential of diffusion chronometry in garnet–cordierite—an unconventional but powerful mineral pair—to quantify timescales of lower-crustal thermal evolution, and to discriminate between transient thermal perturbations and long-lived hot orogenic conditions in Proterozoic continental crust.