Goldschmidt 2023 Abstract
https://doi.org/10.7185/gold2023.18294

Zirconium isotopic compositions of igneous zircon reveal dominantly equilibrium crystallization conditions throughout Earth's history

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The variations of Zr isotopic compositions in zircon are increasingly considered as a potential tracer of planetary differentiation and continental crust evolution. Although resolvable variations of $\delta^{94/90}Zr_{IPGP\text{-}Zr}$ were documented in igneous zircon [1–3], ab initio calculations suggest that high temperature igneous processes, in particular equilibrium zircon crystallization, only result in negligible Zr isotopic fractionation [4,5]. Moreover, data from sedimentary rocks indicate that the upper continental crust had a homogeneous Zr isotopic composition across geological time [6].

We have analyzed $\delta^{94/90}Zr_{IPGP\text{-}Zr}$ of both standard and unknown zircons from >30 igneous rocks by fs-LA-MC-ICP-MS, to cover a wide spectrum of magma compositions (various granitoid, volcanic and mafic rocks; carbonatite; kimberlite), geodynamic settings and periods of Earth's history (from the Paleoarchean to the Pliocene). The results show that the reproducibility of the method is about ± 0.16‰ (2 standard deviations (SD)), which is theoretically sufficient to resolve the isotopic variations described in natural zircon (one, up to several ‰).

However, the analyzed zircons fall within a restricted range of $\delta^{94/90}Zr_{IPGP\text{-}Zr}$ between -0.15‰ and +0.25‰, with most of the dataset showing values overlapping within uncertainties. Moreover, our entire dataset yields a weighted mean value of $\delta^{94/90}Zr_{IPGP\text{-}Zr} = +0.07 \pm 0.14$ (2 SD, n = 339) which matches the average value of +0.077 ± 0.058 obtained for the upper continental crust [6]. These results suggest that Zr isotopic fractionation during zircon crystallization is limited on a global scale, i.e. for the most common magma types throughout Earth's history. This probably pinpoints the general prevalence of equilibrium zircon crystallization conditions, whereas documented variations in zircon $\delta^{94/90}Zr_{IPGP\text{-}Zr}$ correspond to diffusion-driven (kinetic) fractionation in out-of-equilibrium systems [1,4,5].

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