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Early Earth Redox States and the Onset of Mobile-lid Tectonics Recorded by Jack Hills zircon

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Mobile-lid tectonics is a defining feature of the modern Earth, yet the origin of this fundamental process remains uncertain. Detrital zircon crystals provide the most complete record of Earth's early crust and have yielded invaluable insight into early Earth magmatic processes, however, their potential to elucidate ancient metamorphic environments remains largely untapped. From a collection of Jack Hills zircon, grains with distinct metamorphic rims were identified. These domains truncate or embay the primary zonation of their cores and display bright cathodoluminescence, features typical of overgrowths formed during high-grade metamorphism. We combined U XANES oxybarometry [1] with U-Pb and trace element analysis to investigate the igneous cores and metamorphic rims of these samples.

Igneous cores (4.15-3.36 Ga) record consistent, moderately oxidized magma conditions (FMQ-0.3 ± 0.6) [ΔFMQ denotes the log-unit deviation from the fayalite-magnetite-quartz redox buffer], supporting models of efficient mantle convection during the Hadean and challenging the idea that the early Earth was highly reduced. Zircon rims define distinct populations reflecting growth in contrasting metamorphic environments. One group, present throughout the Hadean-Archean, records high fO_2 (~FMQ+2), high temperatures (~700-940 °C), and enrichments in LREE. These signatures likely reflect formation from anatectic melts generated during breakdown of hydrous minerals at high T/P conditions (≥500 °C/GPa). A second group appears in the Archean (~3.35 Ga) that records lower fO_2 (~FMQ), lower temperatures (~640-820 °C), and weakly negative to positive Eu anomalies. These characteristics suggest growth at high pressure, beyond the limit of plagioclase stability, at low T/P conditions (<500 °C/GPa). Additionally, the REE patterns of the low-fO_2 rims resemble zircon from modern high-pressure metamorphic terranes, supporting their formation at great depth. While high T/P conditions in the Hadean are consistent with single- or mobile-lid processes, low T/P metamorphism is associated with collisional settings and large-scale plate underthrusting, a scenario which requires horizontal plate motions. Together, these findings imply that Earth's mantle reached near-modern redox states by 4.15 Ga and that mobile-lid tectonics was active by the early Archean [2].

[1] Houchin et al. (2024), *Geochimica et Cosmochimica Acta*
[2] Houchin et al. (2026), *PNAS (in press)*