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A South African Zircon Record of Hadean Surface Oceans and Eoarchean Emergent Land

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The evolution of Earth's early hydrosphere and the extent of emergent land during the Hadean to Paleoarchean remain poorly constrained, limiting our understanding of when liquid water became widespread and how early water-crust interactions shaped habitable environments. Zircon oxygen isotopes provide a direct tracer of such processes in this interval. Here we present zircon $\delta^{18}O$ and trace element data from 4.2 to 3.3 Ga detrital zircons from the Green Sandstone Bed, South Africa, to evaluate early fluid-driven alteration and link shifts in water-crust interaction to changes in tectono-magmatic processes.

Zircons older than 3.85 Ga yield a mean $\delta^{18}O$ of 6.0 ± 0.4‰, slightly above mantle values. Clear supracrustal signatures are present by 4.14 Ga, providing a third locality, alongside Jack Hills and South China, that records interaction with low-temperature surface waters in the Hadean. Together, these datasets suggest that liquid water was present at Earth's surface early in its history.

Beginning at 3.85 Ga, new zircon populations record a shift from long-lived, mantle-derived protocrust toward flux melting, higher-pressure crystallization, and juvenile felsic additions, consistent with proto-continental growth. This shift coincides with $\delta^{18}O$ values as low as ~2‰. Unlike the main zircon population, these low-$\delta^{18}O$ grains retain mantle-like and shallow-melting trace element signatures, implying melts sourced from mantle upwelling and emplaced as shallow magma bodies. Such near-surface melt storage would have provided sustained heat for high-temperature hydrothermal circulation, producing isotopically light crust that was subsequently assimilated by these melts. The most extreme depletions are difficult to reconcile with alteration in a fully marine setting such as a mid-ocean ridge. Instead, their signatures most closely resemble zircons from modern terrestrial rifts or hotspots, where upwelling melts interacted with continental basement and drove circulation of isotopically light meteoric fluids.

Collectively, our results are consistent with locally emergent proto-continental crust by ~3.85 Ga, persisting intermittently or continuously for at least 250 Myr. Even if limited in areal extent, such environments would have intensified silicate weathering, enhanced nutrient delivery to the oceans, and expanded terrestrial to shallow-marine ecological niches relevant to early life.