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Early Earth System and Planetary Memories in Detrital Zircon Archives

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Earth's earliest history has been largely erased, leaving detrital zircon as the only continuous archive extending back to ~4.4 Ga. However, related studies commonly focus on isolated geosphere processes, lacking a systematic perspective on cross-sphere coupling dynamics. Simultaneously, rapid advances in comparative planetology provide an unprecedented context to re-evaluate these terrestrial records. Here, we integrate advances in both terrestrial and extraterrestrial zircon research with broader planetary and geological evidence to reveal a fundamental, planetary-scale dynamic reorganization between ~4.0 and ~3.2 Ga.

Detrital zircon age spectra, coupled with Hf-O isotopic and trace element signatures, indicate that the Hadean Earth was characterized by episodic crust-mantle differentiation, transient primitive mantle influxes, prolonged crustal reworking, and limited deep recycling of supracrustal materials. These features likely reflect the dominance of a stagnant-lid regime. From ~4.0 Ga onward, although the geodynamic shift occurred diachronously across multiple cratons, a defining feature was the onset of sustained crust-mantle differentiation, accompanied by juvenile mantle input and intensified supracrustal recycling. Concurrently, an active hydrological cycle was established, facilitating the transport of surface waters into deep magmatic systems. The partial pressure of reducing gases in the atmosphere declined progressively, and Earth witnessed its earliest evidence for organic life, indicating an unprecedented enhancement of biosphere-atmosphere-hydrosphere-lithosphere coupling.

Such a transitional interval coincides with major internal and surface changes on planetary neighbors, including sustained impact modification and multi-stage magmatic activity on the Moon, as well as geomorphological reshaping, climatic fluctuations, and episodic hydrological shifts on Mars. The temporal alignment of these events points to a shared window of planetary-scale dynamic reorganization. Subsequently, only Earth transitioned into a recycling-dominated mobile-lid regime with strengthened cross-sphere coupling, establishing the dynamical basis for long-term habitability. By contrast, Mars and the Moon evolved toward long-term stagnant and volatile-depleted states. On this basis, detrital zircon archives constitute an integrative planetary record linking deep interior dynamics to surface system evolution, providing a unified framework for evaluating the common origins and divergent evolutionary fates of terrestrial planets.