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Progressive evolution of Archean orogens: From juvenile accretion to deep crustal reworking

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How continental lithosphere grew, matured, and attained long-term stability during the Archean remains a fundamental question in Earth evolution. In particular, the evolution of orogenesis—from juvenile crust accretion to the formation of stabilized, thickened continental domains—remains poorly understood. The late Archean time interval likely witnessed a transition to plate tectonics, yet the temporal progression of pressure–temperature (P–T) regimes, magma sources, and crustal reworking efficiency within Archean orogens remains elusive. The Rengali Province in eastern India preserves a multi-stage record of crustal evolution spanning ca. 3.0–2.5 Ga. Using integrated petrology and zircon geochemistry data, we document systematic changes that track the progressive transformation of an Archean orogenic system.

The earliest preserved event records felsic crust formation at ca. 3.0 Ga at shallow depths, with largely positive zircon εHf(t) values, indicating dominantly juvenile magmatism with limited involvement of pre-existing crust. This crust was overprinted by high-grade metamorphism at ca. 2.78–2.72 Ga under elevated thermal gradients (~950–1050 °C km^{-1}) at 7.5–8.5 kbar and 790–800 °C, reflecting a hot, accretionary orogenic setup. Coeval felsic magmatism shows a marked broadening of zircon εHf(t), from positive to negative values, indicating enhanced crustal reworking alongside juvenile magmatism. A marked change occurred at ca. 2.5 Ga with emplacement of granitoids characterized by high Cr and Ni contents, requiring interaction with mantle components. Zircon εHf(t) values also shifted to strongly negative values, indicating pronounced reworking of ancient crust with minimal juvenile contribution. Critically, metamorphic and magmatic depths at 2.5 Ga significantly exceed those of earlier events, documenting progressive orogenic thickening.

Our data record a transition from juvenile magmatism and high thermal-gradient metamorphism (ca. 3.0–2.7 Ga) at shallower depths to deep-seated, crust-derived, mantle-interactive magmatism (ca. 2.5 Ga). The progressive increase in crustal recycling, coupled with deepening of tectono-thermal activities and enhanced mantle involvement, suggests that accretionary orogenesis evolved from a relatively hot, thin lithospheric system to a thickened, mature orogenic system by the end Archean. We propose that this pattern - characterized by episodic thermal events with systematically changing P–T conditions, magma sources, and isotopic signatures - may represent a characteristic evolutionary pathway for stabilizing Archean orogens globally.