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Secular change in ambient upper-mantle temperature and the transition from Archean to Proterozoic tectonics: Insights from the rock record and phase equilibria modeling

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There are differences between Archean and post-Archean crust that may be related to Earth's thermal evolution and mechanism of heat loss. The Archean continental crust is dominated by grey gneisses and plutonic complexes of the tonalite–trondhjemite–granodiorite (TTG) suite whereas volcano-sedimentary greenstone belts form only a minor component. The temporal record of apparent thermal gradients retrieved from crustal rocks provides information about secular change in thermal regimes and tectonics. Paleoarchean–Mesoarchean crust generally registers low-to-moderate-P–moderate-to-high-T metamorphic conditions, implying high but uniform apparent thermal gradients of 850–1350°C/GPa; ultrahigh P–T conditions are generally not recorded. This record is inconsistent with one-sided subduction, which generates an asymmetric thermal structure that is registered in the crust as two types of metamorphism with contrasting apparent thermal gradients. In the Mesoarchean–Neoarchean, the sporadic appearance of two types of metamorphism with contrasting apparent thermal gradients—eclogite–high pressure granulite metamorphism with apparent thermal gradients of 350–750°C/GPa and granulite–ultrahigh temperature metamorphism with apparent thermal gradients of 750–1500°C/GPa—marks a transition to one-sided subduction and plate tectonics as the dominant geodynamic regime.

Although the thermal structure of the mantle in the Archean is poorly constrained, petrological data and thermal evolution models suggest ambient upper-mantle potential temperatures (Tp) in the Archean were significantly hotter than the present day. Ambient upper-mantle temperature affects the tectonic regime and style of orogenesis. Results of 2-d numerical experiments show that one-sided subduction is stabilized by stronger lithosphere consequent upon reduced melt flux from underlying asthenospheric mantle as Tp declined to <200°C warmer than present-day by the end of the Archean. Furthermore, higher ambient Tp would have led to extensive melting of the mantle and the production of a thick MgO-rich primary crust, perhaps up to as much as 45 km thick if Tp was >1600°C, that probably formed by over- and intra-accretion of magmas, akin to modern oceanic plateaux. Thick crust inhibits subduction. Here we model the equilibrium mineral assemblages developed within a wide range of metamorphosed (hydrated) primary crust compositions and their complementary residues, assuming a Moho temperature of 1000°C. Using calculated densities based on these mineral assemblages, we show that ultra-thick primary crust in the Paleoarchean is denser than the underlying depleted mantle and capable of delamination. The transition to dominantly steep-slab modern subduction and plate tectonics occurred during the Paleoproterozoic when ambient Tp had fallen to <1600°C. These results are consistent with the scarcity of eclogites preserved in the orogenic rock record before 1.9 Ga, whereas eclogites recording metamorphic pressures up to 2.0 GPa become common in the Paleoproterozoic.