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INVITED CENTENNIAL ARTICLE

Secular change in metamorphism and the onset of global plate tectonics

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ABSTRACT

On the contemporary Earth, distinct plate tectonic settings are characterized by differences in heat flow that are recorded in metamorphic rocks as differences in apparent thermal gradients. In this study we compile thermal gradients [defined as temperature/pressure (T/P) at the metamorphic peak] and ages of metamorphism (defined as the timing of the metamorphic peak) for 456 localities from the Eoarchean to Cenozoic Eras to test the null hypothesis that thermal gradients of metamorphism through time did not vary outside of the range expected for each of these distinct plate tectonic settings. Based on thermal gradients, metamorphic rocks are classified into three natural groups: high $\mathrm{d}T/\mathrm{d}P$ [>775 °C/GPa, mean ~1110 °C/GPa (n = 199) rates], intermediate $\mathrm{d}T/\mathrm{d}P$ [775–375 °C/GPa, mean ~575 °C/GPa (n = 127)], and low $\mathrm{d}T/\mathrm{d}P$ [<375 °C/GPa, mean ~255 °C/GPa (n = 130)] metamorphism. Plots of T, P, and T/P against age demonstrate the widespread occurrence of two contrasting types of metamorphism—high $\mathrm{d}T/\mathrm{d}P$ and intermediate $\mathrm{d}T/\mathrm{d}P$—in the rock record by the Neoarchean, the widespread occurrence of low $\mathrm{d}T/\mathrm{d}P$ metamorphism in the rock record by the end of the Neoproterozoic, and a maximum in the thermal gradients for high $\mathrm{d}T/\mathrm{d}P$ metamorphism during the period 2.3 to 0.85 Ga. These observations falsify the null hypothesis and support the alternative hypothesis that changes in thermal gradients evident in the metamorphic rock record were related to changes in geodynamic regime. Based on the observed secular changes, we postulate that the Earth has evolved through three geodynamic cycles since the Mesoarchean and has just entered a fourth. Cycle I began with the widespread appearance of paired metamorphism in the rock record, which was coeval with the amalgamation of widely dispersed blocks of protocontinental lithosphere into supercratons, and was terminated by the progressive fragmentation of the supercratons into protocontinents during the Siderian–Rhyacian (2.5 to 2.05 Ga). Cycle II commenced with the progressive reamalgamation of these protocontinents into the supercontinent Columbia and extended until the breakup of the supercontinent Rodinia in the Tonian (1.0 to 0.72 Ga). Thermal gradients of high $\mathrm{d}T/\mathrm{d}P$ metamorphism rose around 2.3 Ga leading to a thermal maximum in the mid-Mesoproterozoic, reflecting insulation of the mantle beneath the quasi-integral continental lithosphere of Columbia, prior to the geographical reorganization of Columbia into Rodinia. This cycle coincides with the age span of most anorogenic magmatism on Earth and a scarcity of passive margins in the geological record. Intriguingly, the volume of preserved continental crust of Mesoproterozoic age is low relative to the Paleoproterozoic and Neoproterozoic Eras. These features are consistent with a relatively stable association of continental lithosphere between the assembly of Columbia and the breakup of Rodinia. The transition to Cycle III during the Tonian is marked by a steep decline in the thermal gradients of high $\mathrm{d}T/\mathrm{d}P$ metamorphism to their lowest value and the appearance of low $\mathrm{d}T/\mathrm{d}P$ metamorphism in the rock record. Again, thermal gradients for high $\mathrm{d}T/\mathrm{d}P$ metamorphism show a rise to a peak at the end of the Variscides during the formation of Pangea, before another steep decline associated with the breakup of Pangea and the start of a fourth cycle at ca. 0.175 Ga. Although the mechanism by which subduction started and plate boundaries evolved remains uncertain, based on the widespread record of paired metamorphism in the Neoarchean we posit that plate tectonics was established globally during the late Mesoarchean. During the Neoproterozoic there was a change to deep subduction and colder thermal gradients, features characteristic of the modern plate tectonic regime.

Keywords: *P*-*T*-age of metamorphism, thermal gradients, subduction, geodynamic cycles, blueschist, eclogite; Invited Centennial article; Review article