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Breakdown of primordial layering in the early Earth: implications for tectonic regime and ancient geochemical signals through time

ANNA J. P. GÜLCHER[1], MAXIM D. BALLMER[2] AND PAUL J. TACKLEY[3]

[1]Institute of Geophysics, ETH Zürich
[2]University College London
[3]ETH Zürich

Presenting Author: anna.guelcher@erdw.ethz.ch

Already during the earliest stages of Earth's evolution, mantle heterogeneity is thought to arise from fractional crystallization of a deep magma ocean. $MgSiO_3$ bridgmanite is the first cumulate to crystallize from the magma ocean, potentially forming the most ancient heterogeneity in the mantle. The resulting primordial layering sequence determines the initial state of the lower mantle, and thereby greatly influences the subsequent style of mantle convection. Evidence from short-lived nuclide decay systems suggests that early-formed ancient mantle heterogeneities have been preserved until the present-day. Yet, it remains challenging to reconstruct mantle evolution from the post-magma ocean to present-day state.

Here, we apply numerical models of mantle convection in 2D spherical annulus geometry to investigate the style of material mixing in Earth's mantle through time. Primordial heterogeneity (i.e., enhanced in the strong $MgSiO_3$ mineral) is initialized as chemical layering in the mantle, while additional heterogeneity is introduced over time by subduction of crustal rocks. We characterize the scale and distribution of chemical heterogeneity in the mantle, and their effect on convective patterns and tectonic behavior.

All our numerical models involve the breakdown of the ancient compositional layering ("overturn") at ~3-3.5 Ga, marking the beginning of whole-mantle convection. This overturn triggers a major change in tectonic style, shifting from a stagnant or "squishy" lid to modern-style plate tectonics. It also allows deep-rooted mantle plumes to reach the upper mantle, and crustal materials to be subducted to the lowermost mantle, for the first time. We quantify upper-mantle processing of primordial materials, and compare our model predictions with isotopic ratios (i.e., $^{182}W/^{184}W$ and $^{142}Nd/^{144}Nd$) of Archean and modern igneous rocks. The generally decreasing trend of the maximal isotopic anomalies during the Archaean and through the present-day, as evident in the rock record, is consistent with our results in terms of primordial material entrainment. Moreover, if the primordial layer was relatively oxidized, the predicted whole-mantle overturn at ~3-3.5 Ga may have contributed to the Great Oxidation Event. Indeed, such an overturn can simultaneously explains key geological and geochemical observations; it may have shaped Earth's tectonics, and even the evolution of the atmosphere and life.