Mantle mixing and evolving tectonic states: An optimal phase?

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Growing geodynamic and geochemical evidence suggests that plate tectonics may not have operated on the early Earth. Higher mantle temperature favors an initial single plate mode of tectonics (stagnant-lid). This state can evolve over time into a mobile-lid (plate tectonics) state as radiogenic heat sources decay. Accordingly, information from current observations and processes have the potential of sampling portions of the Earth that has both formed under and been modified by differing tectonic regimes. Here we explore internal velocity structures (a proxy for mixing) in 3D spherical models of mantle convection which incorporate radially stratified and temperature-dependent viscosities.

Early in the geologic lifetime of a terrestrial planet, high mantle temperatures favor stagnant-lids. For equivalent parameter values stagnant-lids have lower internal velocities, shorter convective path lengths, and higher potential temperatures than mobile-lids. As radiogenics are tapped, a stagnant-lid may yield into a high temperature mobile-lid state. The velocity structure of the upper and lower mantles of these systems show strong radial variation, with a high velocity high potential temperature upper mantle and lower velocity, lower potential temperature lower mantle. As radiogenics further decrease, the upper and lower mantles show higher degrees of coupling, and larger wavelength velocity structures develop. At low temperatures the system is dominated by long wavelength, moderate velocity and temperature structures, but a low velocity and temperature background mantle.

We can infer from these results that early planets are likely to be chemically stratified from inefficient mixing of the interior. As the system evolves, middle aged plate-tectonic planets will begin to mix the previously stratified mantle, with increasing efficiency as internal temperatures decrease. As the planet continues to age, mantle scale velocity structures develop, strengthening communication between upper and lower mantles. However, the total velocity of the system decreases with decreasing temperature, terminating the ability of the system to mix over geologic time scales. These results strongly suggest that there are optimal phases in the evolution of a planet for effective mixing of mantle reservoirs, and offer constraints and predications on the availability of these reservoirs to be sampled over time.