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New Insights from the Perspective of Gravitational Work for Current Mantle Energetics

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The Earth's mantle convects to lose heat [Holmes, 1931], so driving plate tectonics [Turcotte and Oxburgh, 1967]. We use the informative perspective of considering transformations between gravitational and mechanical energy to revisit the energetics of mantle convection. To do this we explore a combination of analytical theory, observations on present plate subduction, several thought experiments on energy transformations within a compressible convecting mantle, and a suite of fully compressible (ALA) 2-D numerical experiments. These illustrate that conversions between gravitational energy, viscous dissipation, and adiabatic p-V work arise naturally in mantle convection, and yield new insights on the current energetics of the mantle. The basic insight is that the gravitational energy released by buoyant plume ascent and dense slab descent is directly transformed into viscous dissipation in both an incompressible as well as a compressible convecting mantle, as we prove with theortical arguments and numerical demonstrations. We briefly explain why this self-evident insight became a false controversy.

Significant gravitational energy is created by the cooling of oceanic lithosphere at the top of hotter, less dense mantle. When slabs subduct, in an Earth-like (PREM-like) mantle this gravitational energy is mostly ($\sim$83%) transformed into heat by viscous dissipation (The other $\sim$17% will be immediately transformed back into gravitational energy during the expansion work associated with internal dissipation-linked heating.). At present, the potential gravitational energy release by current slab subduction is comparable to the heat produced by radioactive decay within the mantle. This ratio of gravitational work to radioactive energy production within the mantle is much higher than the 'steady-state' $\sim$17% ratio that is sustainable by internal heating of a PREM-like mantle, implying that the mantle is currently in a phase of much higher than average lithosphere subduction and transient mantle cooling that is associated with an above-average rate of internal viscous-dissipation heating. Furthermore, only a small fraction of the gravitational energy released by slab descent can be stored at internal density interfaces, as we demonstrate with a series of numerical and thought experiments.

While the effects of (conductive) slab cooling are localized near the slabs, the mantle dissipation-heating induced by slab-descent may preferentially heat the hottest, weakest regions of the mantle. It is unlikely for viscous dissipation to be concentrated in high-viscosity sinking slabs, or even uniformly distributed throughout Earth's mantle. Rather, if connected low-viscosity circuits exist, then dissipation will be concentrated within these regions. Focused viscous dissipation within weaker- and hotter-than-normal regions of the mantle may play an important local role in the heating of these boundary layers, and in enhancing low-viscosity D", upwelling plume, and asthenosphere flow structures within mantle flow. Since the gravitational energy of the lithosphere is only released when a plate subducts, the onset of a major new subduction zone could be soon followed by globally enhanced plume and asthenosphere melting. The Cretaceous 'superplume' episode may be an example of such a period, with the post-Cretaceous mantle still being in a period of faster-than-average heat loss and seafloor spreading. Finally, we speculate that there may even be a possible physical mechanism for laterally variable viscous-dissipation heat generation within D" to be an important energy source for convection in the outer core. Could core convection be largely top-driven by variable heatflow at its top surface, and this be the 'missing' energy source to drive the core dynamo?! If true, this possible driving force for the dynamo has the potential to further clarify why superplume events are causally-linked to long epochs of non-reversing magnetic fields (Courtillot and Olson, 2007).