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Transitions in tectonic mode based on calculations of self-consistent plate tectonics in a 3D spherical shell

Hein van Heck and Paul Tackley
ETH Zürich, Earth Science, Zürich, Switzerland (hvanheck@erdw.ethz.ch)

In the past decade, several studies have documented the effectiveness of plastic yielding in causing a basic approximation of plate tectonic behavior in mantle convection models with strongly temperature dependent viscosity, strong enough to form a rigid lid in the absence of yielding. The vast majority of such research to date has been in either two-dimensional, or three-dimensional cartesian geometry. Also, scalings for mixed internally and bottom heated convection are not well established.

In our previous study (van Heck and Tackley, 2008), mantle convection calculations were performed to investigate the planforms of self consistent tectonic plates in three-dimensional spherical geometry. We found, for internally heated convection and fixed Rayleigh number, that when the yield stress of the lithosphere is low a "great circle"-subduction zone forms. At low-intermediate yield stresses plates, spreading centers and subduction zones formed and were destroyed over time. At high-intermediate yield stresses two plates form, separated by a great circle boundary that is a spreading centre on one side and a subduction zone on the other side. At high yield stresses a rigid lid was observed.

Here, the planforms found by van Heck and Tackley (2008) are investigated further, leading to a more general understanding of how different parameters determine which planform prevails. In particular the transition from the mobile to the rigid lid is investigated. New calculations are performed to investigate the effect of varying Rayleigh number and different internal/bottom heating ratios. The results are compared to newly developed analytical scalings for boundary regimes.

These scalings can form a basis to study the tectonic evolution of a cooling planet. As radioactive heat production decreases over time the tectonic mode (e.g. changes in plate size, rigid lid convection to tectonic plates, smoothly evolving plates to more episodic, time dependent, tectonics) is likely to change. The results show that with decreasing internal heating rate (H) the transition from rigid to mobile lid occurs at higher lithospheric yield stress, meaning that for a cooling planet it becomes more likely to have active plate tectonics over time. Also, plate tectonics is more likely at lower Ra. In more detail, provided the dimensionalisation of stress is done via the viscosity, the (dimensional) critical yield stress scales as $Ra^{-\frac{1}{3}}$. A constant critical yield stress scales as H^{-1} while yield stress increasing linearly with depth (friction coefficient) is independent of H.

In principle, this allows us to apply the scalings to the present day Earth as well as to its history. Our scalings can form a basis to describe the thermal-tectonic evolution of Earth, Mars and Venus as well as terrestrial extra-solar planets. This however, would need to include scalings for heat flux as well. Grigné et al. (2005) showed that surface heat flux depends on the wavelength of convection so the scalings for heat flux will not only depend on the internal/bottom heating ratio but also on the tectonic planform since the wavelength of convection (i.e. plate size) changes for different planforms (van Heck and Tackley, 2008).