Mantle Convection, Stagnant Lids and Plate Tectonics on Super-Earths

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Abstract

The discovery of extra-solar super-Earths has prompted interest in their possible mantle dynamics and evolution, and in whether their lithospheres are most likely to be undergoing plate tectonics like on Earth, or be stagnant lids like on Mars and Venus. The origin of plate tectonics is poorly understood for the Earth, likely involving a complex interplay of rheological, compositional, melting and thermal effects, which makes it impossible to make reliable predictions for other planets. Nevertheless, as a starting point it is common to parameterize the complex processes involved as a simple yield stress that is either constant or has a Byerlee's law dependence on pressure (e.g., [1] and [2] in 3D cartesian geometry; [3] in 3D spherical geometry).

For such a simple description, scaling with planet size is expected to depend on heating mode (internal versus basal) and lithospheric strength profile. Simple back of the envelope scaling laws (e.g., following [4]) ignoring the pressure-dependence of physical properties such as density and thermal expansivity, suggest, however, that the threshold for plate tectonics (i.e., yield stress or friction coefficient) does not depend strongly on planet size, and plate tectonics is equally likely or more likely for larger planets. In detail, plate tectonics is equally likely for internally heated convection and basally heated convection when a depth dependent yield stress is used, and more likely for basally heated convection when a constant yield stress is used. Scalings that take into account pressure-related changes in physical properties [5] make a similar prediction for predominantly internally-heated convection.

Because the simplifying assumptions made in developing analytical scalings may not be valid over all parameter ranges, numerical simulations are needed; the one numerical study on super-Earths to date [6] finds that plate tectonics is less likely on a larger planet, in apparent contradiction of analytical results. To try and understand this we here present new calculations of yielding-induced plate tectonics as a function of planet size, increasing the radius of the planet up to twice Earth radius. With the planet radius we scale the non dimensional parameters Rayleigh number, internal heating rate, yield stress and yield stress gradient accordingly. Calculations are focussed on the idealized endmembers of internal heating or basal heating as well as different strength profiles, which we compare to analytical scalings.

Results of calculations performed in 2D cartesian geometry (figure 2 and 3) indicate some first order similarity to simple scalings though some differences exist. In order to investigate the discrepancy between the analytical scalings and this set of calculations we perform a second set of calculations, using a 2D spherical annulus geometry (figure 1) and a more realistic rheology and convective vigour.

In Earth, physical properties such as density, thermal expansivity, thermal conductivity and viscosity change strongly with pressure such that their values change substantially between the surface and the CMB, and many modelling studies have shown that this has a strong effect on convection. On super-Earths this
Figure 2: Overview of the results of the calculations using the endmember; basally heated, constant yield stress. Performed in 2D cartesian geometry, aspect ratio 4. At low yield stresses a mobile lid develops, at high yield stress a rigid lid. With increasing planet size the minimum (dimensional) yield stress at which a rigid lid can prevail increases, suggesting that, in this endmember case, plate tectonics is more likely on super-Earths than it is on Earth.

Figure 3: Overview of the results of the calculations using the endmember; internally heated, constant yield stress. Performed in 2D cartesian geometry, aspect ratio 4. With increasing planet size the minimum (dimensional) yield stress at which a rigid lid can prevail stays constant, suggesting that, in this endmember case, plate tectonics is equally likely on super-Earths then it is on Earth.

References


