Hysteresis in mantle convection: Plate tectonics systems

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[1] We use simulations of mantle convection with surface yielding to show that multiple tectonic regimes are possible for equivalent system parameter values. Models with the same lithospheric strength parameters and the same vigor of convection can display different modes of tectonics. Within the region of multiple solutions, the evolutionary pathway of the system is the dominant factor that determines the tectonic mode (e.g., whether mantle convection operates in a plate tectonic like mode). The extent of the multiple regimes window is found to increase with the temperature-dependent viscosity contrast across the system. The implication for models that seek to predict the tectonic regimes of planets is that the temporal evolution of the planet needs to be taken into account. A further implication is that modeling studies can lead to different conclusions regarding the tectonic state of a planet, extra-solar planets in particular, despite the final model parameter values remaining equivalent. **Citation:** Weller, M. B., and A. Lenardic (2012), Hysteresis in mantle convection: Plate tectonics systems, *Geophys. Res. Lett.*, *39*, L10202, doi:10.1029/2012GL051232.

1. Introduction

[2] Discoveries of large terrestrial (1 Earth mass (M_e) to <10 M_e) extrasolar planets have prompted a range of models to determine the viability of Earth-like plate tectonics on these remote bodies [e.g., *Valencia et al.*, 2006, 2007; *Valencia and O'Connell*, 2009; *O'Neill and Lenardic*, 2007; *Korenaga*, 2010; *van Heck and Tackley*, 2011; *Stein et al.*, 2011]. The models have led to seemingly contradictory conclusions with some predicting that plate tectonics will exist and others arguing that it will not.

[3] The Earth is unique in this solar system in that it exhibits plate tectonics within an active-lid mode of mantle convection. This regime is characterized by active surface deformation, coupled to interior mantle convection, accommodated by brittle faulting along plate boundaries, and associated horizontal surface motions. A more common regime amongst planets and satellites within our solar system is stagnant-lid, which is characterized by little to no horizontal surface motions. A transitional style between plate tectonics and a single plate planet is also possible. This episodic regime is characterized by periods of quiescence, punctuated with episodes of high heat flow and high surface velocities. It has been suggested that Venus and Enceladus may be operating in this regime [e.g., *Turcotte*, 1993; *Fowler and O'Brien*, 1996; *Moresi and Solomatov*, 1998; *O'Neill and Nimmo*, 2010]. Extending this framework to super-Earths, several groups concluded that a stagnant-lid regime should be favored [*O'Neill and Lenardic*, 2007; *Stein et al.*, 2011] while others predicted that these planets should be in an active-lid mode [*Valencia et al.*, 2007; *Valencia and O'Connell*, 2009; *van Heck and Tackley*, 2011]. *van Heck and Tackley* [2011] argue that the existence of this disparity is due to *O'Neill and Lenardic* [2007] not scaling all parameters (e.g., Rayleigh number, internal heating, yield stress, and yield stress gradient) with the increase in planetary radius. We suggest another mechanism for this disparity.

[4] It has been known that nonlinear systems may contain regions of non-unique solutions, but planetary convecting systems were long thought to not be affected by such windows [e.g., *Turcotte and Schubert*, 2005]. In this paper, we show that for the same parameter values, multiple tectonic regimes are possible. We find that the transgressive transition from active to stagnant-lid conditions occurs at a higher yield stress than the regressive stagnant-lid to active-lid transition, and the extent of this hysteresis is controlled by the viscosity contrast across the system. The implication for models that seek to predict the tectonic regimes of planets is that the thermo-convective evolution of the planet needs to be taken into account.

2. Model and Key Parameters

[5] The convective regime in the mantle of a planet depends on the Rayleigh number (Ra) defined by:

$$Ra = g\rho\alpha\Delta T d^3/\left(\kappa\eta_{0,i}\right) \tag{1}$$

where g is gravity, ρ is density, α is the thermal expansivity, ΔT is the reference temperature drop across the system, κ is the thermal diffusivity, d is layer depth, with η_0 as the reference and η_i as the interior viscosities. The reference viscosity is taken as that of the surface, which is of fixed temperature. The interior mantle temperature is not known a priori (it is part of the model solution). Therefore, the Ra based on internal viscosity can only be calculated after the model has been run to a statistically steady state. The temperature-dependent viscosity is given by:

$$\eta = \exp(-\theta T) \tag{2}$$

with:

$$\theta = Q\Delta T \tag{3}$$

where Q is the activation energy. The convective shear stresses (τ) scales as:

$$\tau_{conv} \sim \eta_i v/\delta \tag{4}$$

where v is the velocity, and δ is the shear length scale, which is comparable to the mantle depth [e.g., *Turcotte and*

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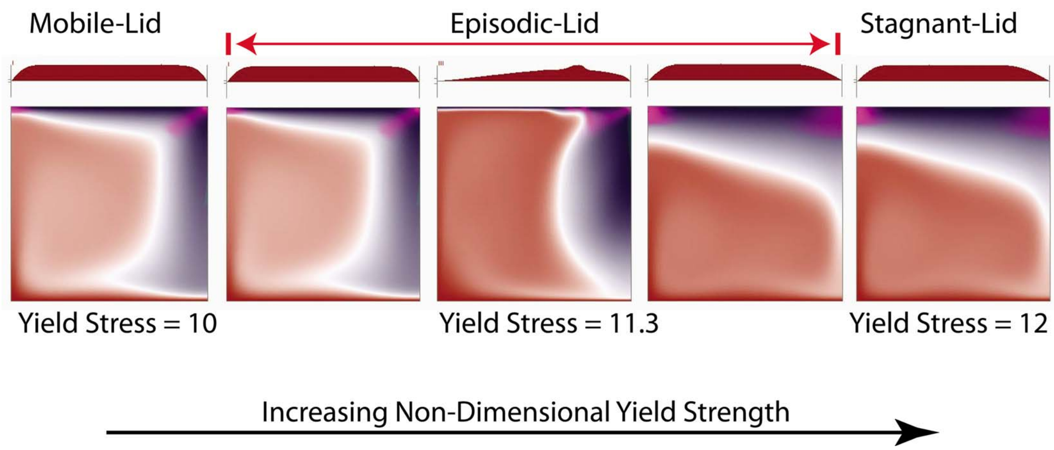

Figure 1. Thermal images from basally heated simulations showing a forward transition between regimes, from active to stagnant through episodic-lid. Each simulation is dependent on results from previous run.

Schubert, 2005; *Solomatov*, 1995]. The dimensionless form of equation (4) is given by:

$$\tau_{conv} = \left(\kappa\eta_i/d^2\right)\tau' \tag{5}$$

[6] To allow plates to form, we apply a yield stress criteria. We follow *Moresi and Solomatov* [1998] and define the yield criteria as follows:

$$\tau_{yield} = c_0 + \mu\rho g z \tag{6}$$

where μ is the coefficient of friction and c_0 is the yield stress at zero hydrostatic pressure, or the cohesive limit. In non-dimensional form equation (6) becomes:

$$\tau'_{yield} = \tau_0 + \tau'_1 z' \tag{7}$$

with the non-dimensionalized cohesion term given by:

$$\tau_0 = \left(d^2/\kappa\eta_0\right) c_0 \tag{8}$$

and the non-dimensional depth dependent stress, or pressure term:

$$\tau_1 = \mu\rho g Ra/(\alpha\Delta T) \tag{9}$$

with Ra defined using the surface viscosity. Equations (4)–(9) allow us to link stresses across the convecting mantle and into the highly viscous and rigid lithosphere.

[7] We explore the effect of pressure dependent yielding on convective regimes in 2D, and 3D using CIITCOM, and CitcomS respectively. For all 2D cases reported, the non-dimensional cohesion term in (7) is set to 0.1, the temperature-dependant viscosity in (2) is set to vary from between 5 and 6 orders of magnitude, and the reference Ra is defined using the surface viscosity, and is set to 10. Thus the Ra defined in terms of the system base increases with increasing temperature-dependent viscosity (from a minimum of 1e6 to a maximum of 3e7). 2D modeling domains consist of a 1:1 aspect ratio with a minimum resolution of 64 $\times$ 64 grid cells and a 3:1 aspect ratio, with wrap-around side boundary conditions, and a minimum resolution of 192 $\times$ 64 grid cells. 3D cases have a temperature-dependant viscosity set to vary between 4 orders of magnitude, the Ra is given at 1e5, and the modeling domain consists of a 32 $\times$ 32 $\times$ 32 grid cell resolution for each of the 12 spherical caps. All 2D and 3D domains are free slip and have constant temperature conditions at the top and base.

3. Results

[8] Figure 1 displays how increasing yield stress leads to regime transitions. As the yield stress increases from the active-lid case, an "episodic-lid" regime is observed. This regime is characterized by rapid pulses of lithospheric overturn, followed by periods of quiescence. As the yield stress is further increased, the internal driving stresses are insufficient to fracture the lithosphere into mobile plates, and the planet enters into a stagnant-lid mode.

[9] To model distinct planetary evolutionary pathways, we run suites of parameter simulations with both increasing and decreasing yield strengths. For each path, the result of the previous higher or lower yield simulations serves as the initial condition for the subsequent case. Results from a range of simulations are presented in Figure 2. The transition from active- to stagnant-lid has a narrow range of yield stress in which episodic behavior is observed. A longer range of episodic behavior occurs when transitioning from high to low yield stress states (regressive pathway; blue arrow in Figure 2). Episodic behavior occurs predominantly in models with higher viscosity contrasts (e.g., $6 \times 10^5 - {\sim}10^6$) and the extent, in terms of the yield stress values, increases with increasing viscosity contrast. A key result from Figure 2 is the divergent paths between increasing versus decreasing yield stress suites. This divergence is associated with a hysteresis gap in which multiple tectono-convective regimes can exist at equivalent parameter values.

[10] The hysteresis, or Tectono-Convective Transition Window (TCTW), is defined as the difference in the yield stress necessary to 1) transition from an active-lid to a stagnant-lid, and 2) transition from a stagnant-lid to an active-lid. As Figure 2 shows, the TCTW widens with increasing viscosity contrast. Figure 3 further quantifies this and indicates that the TCTW obeys a power law relation. The difference in transitional yield stress scales with the viscosity contrast as $Y_w = 0.039\Delta\eta^{0.419}$.

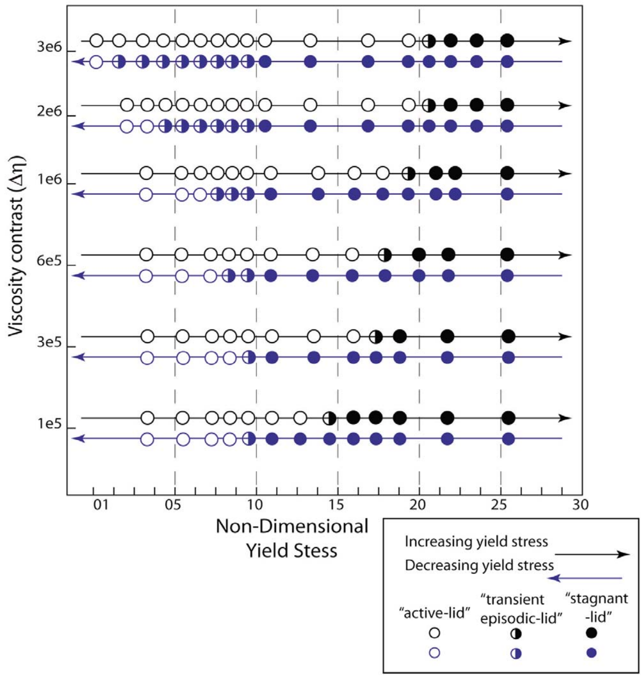

Figure 2. Results for both increasing and decreasing yield strength from active and stagnant-lid cases plotted against viscosity contrast. Open circles indicate active-lid; Closed circles indicate stagnant-lid; and half filled circles indicate episodic-lid.

[11] The existence of a TCTW is robust for models that allow for mixed heating in larger 2D domains (Figure 4a), and in 3D geometries (Figure 4b). The heating ratio (H) is the ratio of the Rayleigh number for purely internally heated convection to the Rayleigh number for pure bottom heating. The temperature-dependent viscosity contrast for 2D is 3e5, and 1e4 for the 3D cases shown. A low viscosity region in the upper mantle is also introduced. Over the top 25% of the 2D domain, the viscosity is lowered by two orders of magnitude if the mantle temperature is above 0.4 of the total system temperature drop. In 3D suites, a viscosity reduction by a factor of 30 is implemented in 20% of the domain in the upper mantle, immediately underlying regions of high viscosity "plates" (grey zones in Figure 4b). The width of the TCTW for the 2D 3:1 suites (a non-dimensional value of 17) and the 3D geometry (a non-dimensional value on the order of 300) are larger than is observed for the pure bottom heating cases with an equivalent temperature-dependent viscosity contrast (e.g., Figure 2).

4. Discussion and Conclusions

[12] The connection between mantle convection and the tectonic regime of planet is a complex subject and many aspects are imperfectly understood. There are a number of effects that have not been explored in our models, such as phase changes [*Nakagawa and Tackley*, 2004], depth-dependant thermal expansivity [*Hansen et al.*, 1993], as well compressible convection [*Dubuffet et al.*, 1999]. Acknowledging that added processes such as the above will affect quantitative results, our simulations do argue that transitions between tectono-convective regimes cannot be predicted based solely on model parameter values. The existence of multiple solution states means that the system allows for a contingent zone within parameter space and, within this zone, the evolutionary history will be a dominant factor in determining the tectonic regime.

[13] To date, the concept that a planets evolutionary history can have an effect on its tectonic regime is surprisingly absent within the exo-planet community. The idea that evolutionary paths and history influence tectonics on Earth has been suggested [e.g., *Gurnis et al.*, 2000]. More recently, the existence of multiple solution states in the convective-tectonic state of the Earth has been argued for using an analytic approach [*Crowley and O'Connell*, 2012]. The simulations of this paper support that conclusion and show that the surface expression of mantle convection is dependent on the directionality of the lid yield stress evolution (a history dependent effect).

[14] The existence of a hysteresis gap (TCTW) can be anticipated based on two scaling issues related to active versus stagnant-lid convection. The first relates to convective stress levels. Active-lid models have a relatively thin conductive lithosphere overlying the mantle. Thick conductive lids, as found in stagnant-lid models, are more inefficient at heat transport. As a result, the interiors are much warmer than mobile-lid counterparts. The increased internal temperature acts to lower mantle viscosity, and as outlined in equation (2), convective stress is proportional to mantle viscosity. Therefore, one would not expect the same yield stress to usher in a transgressive and a regressive transition between regimes for anything other than an isoviscous system.

[15] The other issue relates to the yield stress, and it also suggests that it should be more difficult to move from a stagnant to an active-lid regime, than from an active to a stagnant-lid regime. This can be shown from the yield stress scaling relationships for active-lid (Y_m), and stagnant-lid (Y_s) cases. For a low cohesion material the yield stress

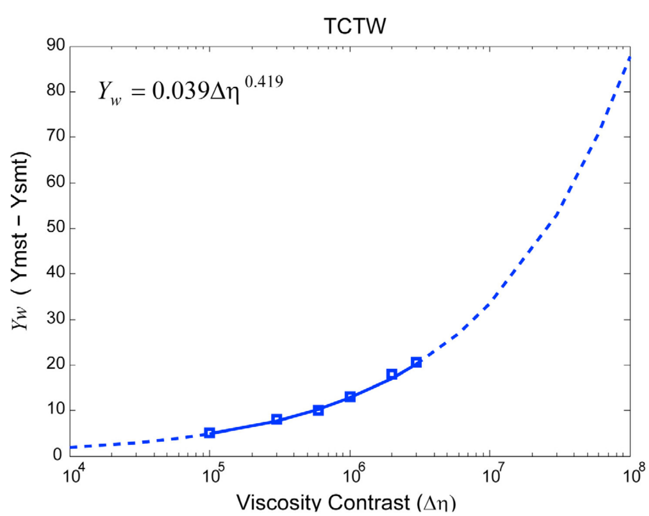

Figure 3. Width of multiple regime domains (TCTW) versus the degree of temperature-dependent viscosity for the 1 × 1 basally heated cases. Y_w is the non-dimensional width of the transition window (i.e., mobile to stagnant transition (Ymst) – stagnant to mobile transition (Ysmt) yield strength). Dashed lines indicate best fit extrapolation.

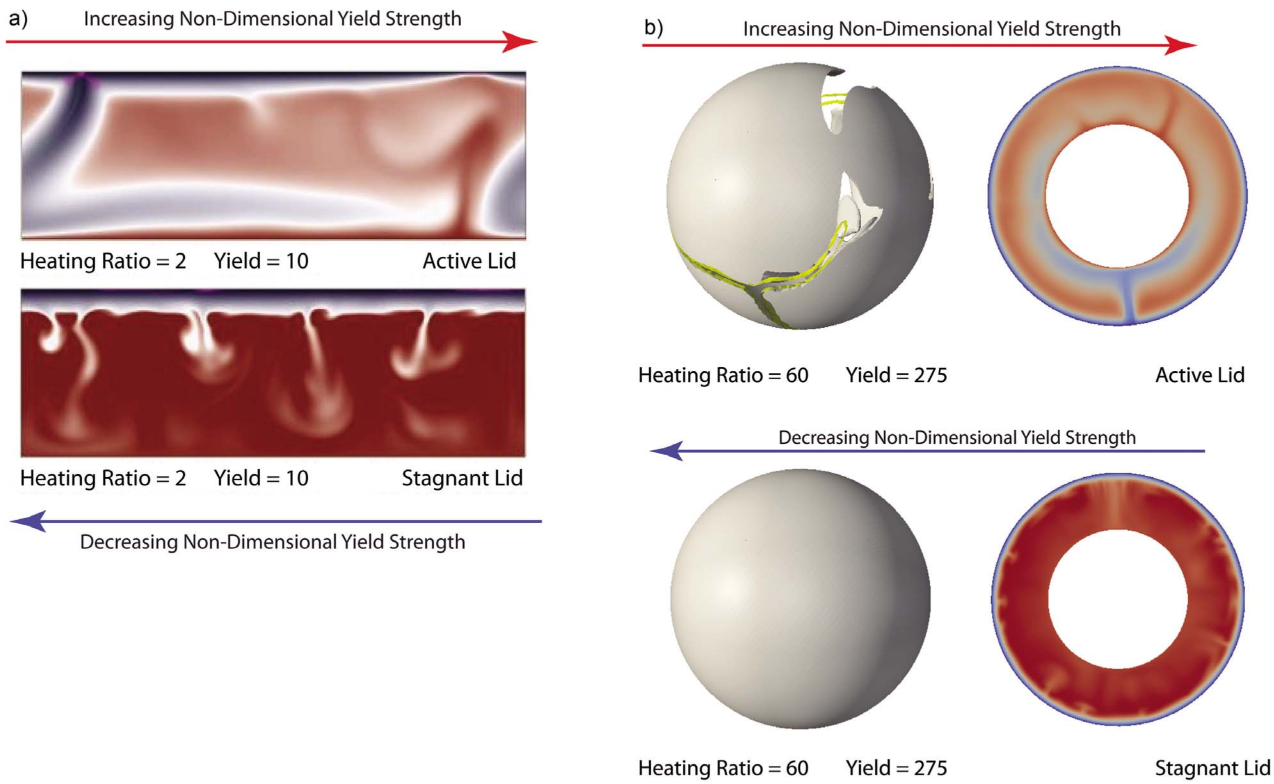

Figure 4. Results from mixed heating simulations showing that for the same control parameters, an active and a stagnant-lid regime exist in more complex (a) 3:1 2D "boxes" and (b) 3D spherical domains. Thermal profiles from the 2D suites given have a viscosity contrast set to 3e5, and viscosity is depth dependent. The spherical case shown indicates regions of high viscosity "plates" (grey shells), regions of upwelling material (yellow bands), and thermal profiles from the CMB to surface. The viscosity contrast is set to 1e4, and is depth dependent. Both simulations have the same control parameter values but different histories in terms of increasing versus decreasing yield stress.

(equation (7)) reduces to $\tau_{yield} = \tau_1 z$, or $\tau_{yield} \propto \delta_m \mu \rho g$ where δ_m is the lid thickness (i.e., the thickness of the lithosphere). The lid thickness varies as $\delta_m \propto Ra^{-1/3}$ for mobile-lid, and $\delta_s \propto Ra^{-1/3}\theta^{4/3} = Ra^{-1/3}\ \ln(\Delta\eta)^{4/3}$ for stagnant-lid cases [e.g., *Solomatov*, 1995]. This predicts that $Y_m < Y_s$ for a non-isoviscous system.

[16] Our results highlight the difficulty of predicting convective regimes throughout this solar system for situations in which geologic history constraints become rare, let alone in extra-solar systems were, at present, no such constraints exist. Figure 2 predicts that the TCTW is expected to widen for more energetic convection (a conclusion that is qualitatively consistent with the analytic results of *Crowley and O'Connell* [2012]). In respect to super-Earths, the TCTW might be expected to be quite large. Thus, the range of non-unique solutions can become expansive. Using the power law fit in Figure 3, a range of TCTW from 0, for isoviscous convection, upwards to 604, for a viscosity contrast of 10^{10}, is predicted. Thus, for larger planets, the TCTW becomes an increasingly important process to consider.

[17] To summarize, different tectonic states are possible for the same planetary parameter values. Within the region of multiple solution states the evolutionary pathway of the system is the dominant factor that determines the tectonic mode. Models that do not acknowledge the potential of this history dependent effect can reasonably only discover one of the three possible tectono-convective regimes that a planet may be operating in. This affects the ability of such models to predict the regime of $\sim$1 M_e sized planets, let alone super massive terrestrial planets. It also suggests that the specifics of how an Earth-like model is scaled up to represent a larger planet can outweigh the effects of physical and chemical parameters in determining the predicted tectonic state (e.g., different predictions are possible if the initial state is taken to be stagnant-lid versus active-lid). It is thus very possible that different modeling groups will be led to different conclusions even if the final model parameter values (e.g., planet size, heat source concentration, yield strength) remain equivalent between groups.

[18] **Acknowledgments.** The Editor thanks David Yuen and an anonymous reviewer for assisting with the evaluation of this paper.

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