Plate Tectonics on Terrestrial Planets: A Hysteresis Of States In Mantle Convection Systems.

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Introduction: Many new discoveries of large terrestrial (1 Earth mass (Me) to < 10 Me) planets have prompted a range of models to determine the viability of Earth like plate-tectonics in operation on these remote bodies. However, previous works have found two conflicting possibilities: 1) Most larger planets will exhibit active-lid tectonics [1-4]; and 2) Most larger planets will be in a stagnant-lid regime [5]. The question to be addressed is: Are both groups correct? In this work, we show that for the same parameter values for a given planet, multiple tectonic regimes are possible.

Scaling: The driving forces that result in lithospheric deformation are primarily generated from viscously induced mantle stresses, which scale as

$$\tau_{conv} \sim \eta_0 v / \delta \quad (1)$$

where v is a velocity scale, η the viscosity of the viscously deforming lithosphere, and δ is a shear layer thickness scale which is comparable to the depth of the convecting mantle. Lithospheric strength is determined by the maximum sustained stress at the brittle-ductile transition, which is calculated through a depth-dependent yield criterion [6]:

$$\tau_{yield} = c_0 + \mu \rho g z \quad (2)$$

where μ is the coefficient of friction, c_0 is the yield stress at zero hydrostatic pressure, or the cohesive limit, ρ is the density, g is gravity, and z is the depth dependant term.

Numerical Models: We explore the effect of variable depth-dependent yield criteria (equation 2) and convective vigor (as determined by the mantle Rayleigh number, Ra) using the CIITCOM finite element code, thoroughly detailed in [7]. The viscosity in these runs is temperature dependent and varies from between 5 to 6 orders of magnitude. The modeling domains consist of 1:1 and 3:1 boxes, with a minimum resolution of 64 x 64 grid cells over each 1x1 portion of the domain. Top and bottom boundary conditions are free slip and have constant temperature. Side boundaries are reflecting for the 1:1 boxes and wrap-around for the 3:1 boxes. Bottom heated and mixed heating cases are explored.

Results and Discussion: We have run a large suite of simulations to map parameter space, testing a range of viscosity contrasts and yield strengths. For each viscosity contrast, two pathways are examined: increasing (from active- to stagnant-lid), and decreasing (from stagnant- to active-lid) yield strengths (Figure 1). In all the model suites, the progression between regimes is accommodated through the episodic regime. In general, the transition from active- to stagnant-lid has a narrow 'window' of yield stress in which a burst of episodic behavior is observed. More robust, longer lived episodic behavior in this parameter space only occurs when transitioning from a high yield stress state, or stagnant-lid conditions (regressive pathway, blue arrow, in figure 1). Furthermore, episodic behavior occurs predominantly in models with higher viscosity contrasts (e.g. 6e5 – 3e6) and the duration (range of yield stresses) is shown to increase with increasing viscosity contrast. An additional suite of model runs, with a viscosity contrast of 3e6, shows a markedly increased transition window. A striking and unavoidable result from Figure 1 is the divergent path, or hysteresis of episodic onset as a function of planetary evolution.

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 1 shows, the TCTW widens with increasing viscosity contrast. Figure 2 shows that the width of the TCTW scales with the temperature-dependent viscosity contrast and has a best fit power law of $Y_w = 0.039 \Delta\eta^{0.419}$.

The TCTW may be physically understood with the consideration of convective conditions within an active, and within a stagnant-lid regime. Since active-lid planets have a relatively thin conductive lithosphere overlying the mantle, they are efficient at transporting heat from the mantle. However, thick conductive lids, as found in stagnant-lid models, are more inefficient at heat transport. As a result, the interiors of such planets are much warmer than the mobile-lid counterparts. The increased internal temperatures acts to lower the temperature dependent viscosity, and as outlined in equation 1, τ is proportional to η. Therefore, all things being held equal, it is implausible to expect the same yield stress to usher in a transgressive and regressive transition between regimes for anything other than an isoviscous system.

Our results are robust for larger mixed heated cases in large modeling domains (Figure 3). These cases also allow for depth-dependent viscosity with a lower mantle viscosity 30 times that of the upper mantle. The temperature dependent viscosity allows for a 3e5 variation. The heating ratio is the ratio of the internal heating Ra to the basal heat Ra.

Conclusion and Future Work: 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 larger the viscosity contrast, the greater the TCTW window becomes, allowing for multiple tectonic regimes to exist for the same parameter values. We are currently running models using CitcomS to explore the yield hysteresis in three dimensional parameter space.

References: [1] Valencia, D. et al. (2007) APJ, 670, L45. [2] Valencia, D. and O'Connel, R. J. (2009) EPSL, 286, 492 – 502. [3] Korenaga, J. (2010) APJ, 725, L43. [4] van Heck, H.J., and Tackley, P. J. (2011) EPSL, 310, 252 – 261. [5] O'Neill, C. and Lenardic, A. (2007) GRL, 34, L19204. [6] Moresi, L. and Solomatov, V. (1998) JGR, 133, 669-682. [7] Byerlee, J. D. (1968) , JGR, 73, 4741 –4650.

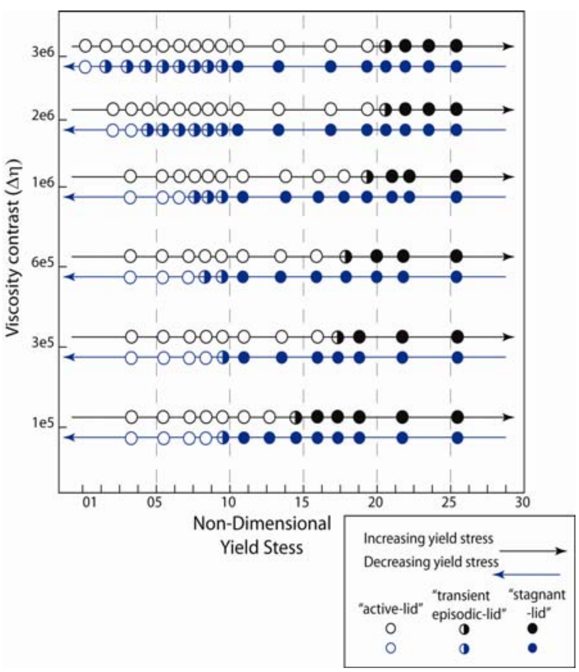

Figure 1. Results for both an increasing and a decreasing yield strength pathway from the respective active and stagnant lid cases plotted against viscosity contrast. Open circles indicate active-lid; Closed circles indicate stagnant-lid; and half filled circles indicate episodic, or transient-lid.

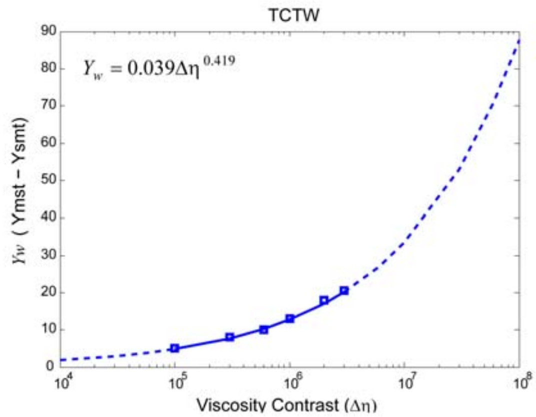

Figure 2. Width of multiple regime domains (TCTW) versus the degree of temperature-dependent viscosity. Y_w is the non-dimensional width of the transition window (i.e. mobile to stagnant transition (Ymst) – stagnant to mobile transition (Ysmt) yield strength). Dashed lines indicate best fit extrapolation.

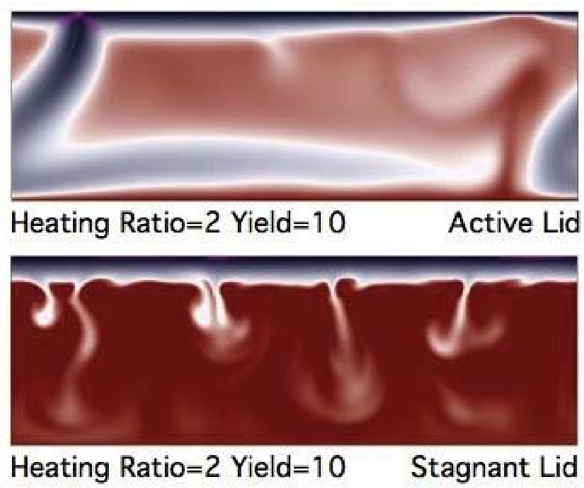

Figure 3. Two mixed heated simulations with the same control parameter values but different histories in terms of increasing versus decreasing yield stress. Note that for the same control parameters, an active and a stagnant lid regime can exist.