Hysteresis of Tectonics Regimes on Terrestrial Worlds, One is Not Enough: Plate Tectonics and Internal Heating Through Time. M. B. Weller[1] and A. Lenardic[1], [1]Department of Earth Science, Rice University, Houston, TX 77005, USA (matt.b.weller@rice.edu, adrian@rice.edu).

Introduction: While plate tectonics is currently observed for the Earth, both the timing of its onset, and the length of its activity have been debated [1]. The uncertainty about the initiation of plate tectonics on the Earth has been extended into the realm of extra-solar super-Earths with groups arguing that a stagnant-lid regime should be favored [2, 3], while others predict that these planets should be in an active-lid mode [4-7]. A significant issue influencing the debate over planetary tectonic styles is the critical importance of initial conditions of the system in determining the tectonic regime. It has been shown that as a convecting system nears the transition between regimes, non-linearities, inherent within the physical system, lead to a hysteresis of states, and the tectonic regime observed depends strongly on the starting state [8-10]. In this work, we expand on previous hysteresis studies [9, 10], evaluating the effects of internal heating pathways (e.g. ageing from hot-start/cold-start conditions) on a planetary body of varying lithospheric yield strengths.

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

$$\tau_{conv} \sim \eta \, v / \delta \ (1)$$

where v is a velocity scale, η is the temperature dependent viscosity, following the general form of $\eta = \exp(-\theta T)$, where $\theta = E\Delta T$, E is the activation energy, ΔT is the reference temperature drop across the system (the temperature drop from the base of the convecting layer to the surface), 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 and is analogous to:

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

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. It has been shown that yielding for mobile-lid regimes follows as $\tau_{ym} \sim Ra_i^{-1/3}$ and for stagnant-lid regimes as $\tau_{ys} \sim Ra_i^{-1/3} \theta^{4/3}$, ensuring that $\tau_{ym} < \tau_{ys}$ for all but iso-viscous systems (e.g. [9]).

Numerical Models: We explore the effect of internal heating rates (Q_0) on the yield criteria (e.g. equation 2) and convective vigor (as determined by the mantle Rayleigh number, Ra) using the CitcomS finite element code with plastic yielding, thoroughly detailed in [11-14]. The range of viscosity variation is set to 1e4 and is both temperature- and depth-dependent, Ra is set at 1e5, and the modeling domain consists of a 32x32x32 grid cell resolution for each of the 12 spherical caps. Top and bottom boundary conditions are free slip and are fixed temperature.

Results and Discussion: Previously, hystereses in mantle convection systems have theoretically and quantitatively been shown to be a significant process in mantle convection simulations [8-10]. We continue to examine the hysteresis parameter space through internal heating pathways. The mantle convection system is initially allowed to transition into a stagnant-lid regime at a high level of internal heating (e.g. $Q_0 = 60$, Yield strength (Ys) = 4.25e4) analogous to a young and hot stagnant-lid planet. As a proxy for ageing, Q_0 is decreased sequentially in a regressive internal heating pathway to a value of 0, and increased from 0 to 60 in a progressive heating pathway. All simulations use the preceding results as initial conditions. This procedure is repeated for a range of increasing lithospheric strengths, from a relatively weak, near transitional stagnant-lid, Ys = 4.25e4, to a relatively strong stagnant-lid, Ys ~ 7.0e4.

The effects of internal heating pathways on the mode of tectonics are discussed in detail for the near transitional stagnant-lid case of Ys = 4.25e4 (Figure 1). Decreasing internal heating values from hot-start ($Q_0 = 60$) stagnant-lid conditions along the regressive pathway are qualitatively in agreement with previous theoretical and 2-D studies [1, 2]: as internal heating drops below ~30, the planetary body transitions first into a short-lived episodic-lid, before settling into a stable mobile-lid regime. With additional decreases in internal heating, the system begins to transition from mobile- to sluggish-lids at Q_0 ~ 16, and finally into an extreme sluggish-lid state (near stagnant-lid conditions) at Q_0 ~ 0. Increasing the internal heating from cold start conditions ($Q_0 = 0$ from the regressive pathway) shows a very rapid return to a mobile-lid, through sluggish-lid behaviors, that remains robust to high levels of internal heating before transitioning back into a stagnant-lid regime (Q_0 ~ 59–60). The Internal Heating Hysteresis (IHH), defined as the magnitude of the region of multiple possible tectonic states in Q_0 parameter space, shows that for nearly all values of internal heating, mobile-lid behavior is possible (IHH ~ 31; Figure 1).

However, as the lithosphere strengthens, the transitions from both stagnant- to mobile-lids within the regressive pathway, and mobile- to stagnant-lids along the progressive path occur for lower values of internal heating (Figure 2). Physically, this can be understood in terms of changes in internal temperature. As Q_0 decreases, τ_{conv} increases (from the exponential dependence of internal viscosity on temperature). Once $\tau_{conv} \sim \tau_{ys}$ in the regressive pathway, the stagnant shell yields, and regime transitions may occur. Conversely, as the internal temperature increases, $\tau_{conv} < \tau_{ym}$, and a stagnant shell forms in the progressive pathway. Thus it can be shown that stronger shells require larger increases in the convective shear stress, which is accommodated through lower levels of internal heating (regressive pathway) to mobilize the shell, or conversely, a lower magnitude increases in internal heating is required to decrease the convective strength such that the system enters into a stagnant-lid regime. The IHH is shown to increase linearly with increasing lithospheric Ys, with the best-fit equation given as $\text{IHH} = 2e^{-4}\ Ys + 21.45$.

Our results show that the tectonic regime a planet exhibits is one of multiple possible stable states, and is a function of its evolutionary history. This hysteresis effect dominates through much of the planet's evolution, with potentially only the ending tectonic conditions determined. In our models as the planet evolves, we find that the range in lithospheric yield strengths that plate tectonics may occur over can be increased by a factor of ~2, dependant on internal heating and starting conditions. A planet that is in a stagnant-lid may transition as it ages into episodic-, and mobile-lid regimes if the lithospheric yield strength is within the threshold value. These results indicate that a transition to plate tectonics can occur throughout the lifetime of a planet, with stronger stagnant-lids potentially transitioning later in their evolution.

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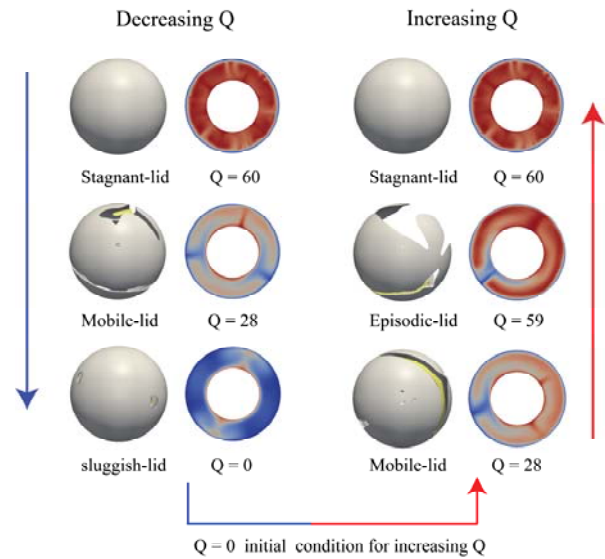

Figure 1: Effects of internal heating on tectonic regimes for a weak stagnant-lid (Ys = 4.25e4). Internal heating (Q_0) is varied from 60 to 0 in the decreasing pathway, and 0 to 60 in the increasing pathway. Each run is divided into a viscosity plot (grey shells are regions of high viscosity "plates" and yellow bands are regions of yielding) and thermal profiles from the CMB to surface. Figure modified from [15].
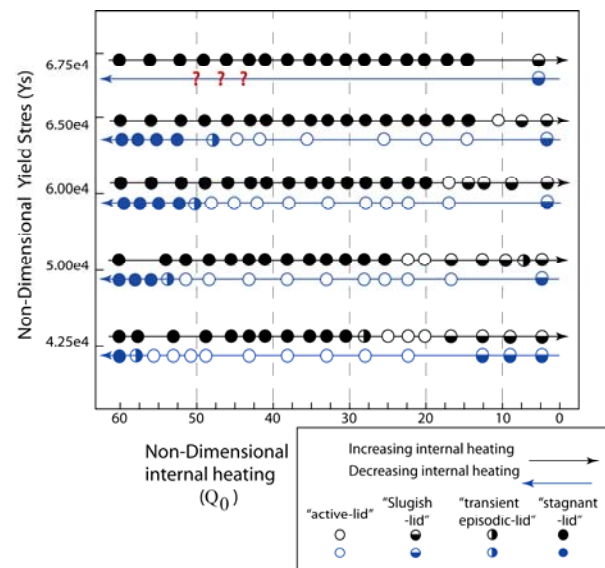

Figure 2: Results for both an increasing and a decreasing internal heating pathway from the respective active- and stagnant- lid cases plotted against non-dimensional internal heating. Black arrows indicate regressive (cooling) pathway, blue arrows indicate progressive (warming) pathway. Open circles indicate active-lid; Closed circles indicate stagnant-lid; Horizontally half filled circles indicate sluggish-lid and; Vertically half filled circles indicate episodic, or transient-lid.