

Sensitivity of Tectonic States to Climatic Perturbations Over Geologic Time: Implications for Terrestrial Worlds. M. B. Weller¹ and A. Lenardic¹, ¹Department of Earth Science, Rice University, Houston, TX 77005, USA (matt.b.weller@rice.edu, adrian@rice.edu).

Introduction: Models for transitions in the mode of planetary tectonics (e.g. plate tectonics to single plate planet) have generally fallen into two categories: 1) those that explore the effects of changing lithospheric properties, e.g. yield stress [1] and; 2) those that explore changes in internal properties, e.g. the degree of internal mantle heating [2]. However, two groups have recently suggested that changes in the long term climate of a planet may result in transitions between tectonic modes [3-6]. Both groups suggest that much warmer surface temperatures over geologic time scales may initiate the cessation of plate tectonics on a terrestrial planet. In this work, we evaluate the effects of changing climatic conditions on the tectonic regime of a planet using 3D mantle convection simulations.

Scaling: The driving stress that results in lithospheric deformation is associated with viscously induced mantle shear stress, which scale as

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

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 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 that is analogous to:

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

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 surface temperature on the balance between lithospheric strength and convective vigor (as determined by the mantle Rayleigh number, Ra) using the CitcomS finite element code with plastic yielding, thoroughly detailed in [1, 7-10]. 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 $32 \times 32 \times 32$ grid cell resolution for each of the 12 spherical caps. Boundary conditions are free slip, and the core-mantle boundary is fixed at a

non-dimensional temperature of 1. All simulations are internally heated.

Results and Discussion: We've conducted a large number of simulations to explore surface temperature/ yield strength (Y_s) parameter space for a hot, young planet, e.g. high internal heating ($Q_0=60$). Surface temperatures are increased sequentially, using the preceding simulation as the initial conditions for the following simulation. This is repeated until the system transitions into a stagnant-lid regime, which occurs at a critical surface temperature for a fixed yield strength value. The onset of both episodic- and stagnant-lid behaviors, as well as the duration of episodic-lid conditions are reported (Figure 1). In general, the transition from active- to stagnant-lid has a narrow 'window' of yield stress in which bursts of episodic behavior can be observed (non-dimensional Y_s values of $\sim 4.25e4 - 3.25e4$) directly before the system transitions into a stagnant-lid regime. More robust, longer lived episodic behavior begins to diverge from the stagnant-lid trend at intermediate Y_s , and occurs over a wider range of lithospheric strength values for increasing values of surface temperatures. That is, the range of lithospheric strengths for which episodic-lid behavior occurs increases with decreasing Y_s or with increasing surface temperatures (T_s) in this region of parameter space (Figure 1).

Early results indicate that decreasing the internal heating rate (e.g. $Q_0=59$, to simulate an ageing planet) leads to an increase in the critical transition T_s from 0.01 to 0.025, and 0.02 to 0.03 for a Y_s of $3.87e4$ and $3.73e4$ respectively. Additionally, the transition to episodic-lid behavior begins to occur at lower critical T_s than the stagnant-lid transition, similar to the divergence seen in intermediate to lower Y_s for higher levels of internal heating. Transitions between regimes cease for values of internal heating of $\sim 45 - 30$ due to the inability of the system to form stable plates for the extremely high values of T_s required (> 0.3). Additionally, a return to mobile-lid behavior by decreasing the T_s from the stagnant-lid transition appears to be unrealistic for this system as it requires a ΔT_s far in excess to the transitioning T_s .

Physically, the mechanism of transition, driven by changes in T_s can be understood from the following. A long term change in the surface temperature leads to a temperature change propagation that affects not only the surface Rayleigh number, but also the total temperature drop, and the temperature-dependent viscosity

contrast across the system. Increasing the surface temperature leads to an increase in temperature that permeates through the lithosphere and into the deep mantle, leading to: 1) a decrease in convective shear stress from the exponential dependence of internal viscosity on internal temperature; and 2) an increase in the thermal boundary layer depth, which increases Y_s and is related to the change in the internal temperature profile and internal Ra (Figure 2). The combination of decreasing convective shear stress and increasing total lid-strength eventually leads to the critical value of T_s (for both episodic- and stagnant-lid conditions) that marks the transition between regimes.

Implications to the Terrestrial Worlds: Our results indicate that the tectonic regime a planet operates within may be set early in its development. A young planet (e.g. high internal heating) is more susceptible to tectonic regime shifts from changes in surface temperature. Early on, transitioning at the critical surface temperature, for relatively high yield strength, can lead to a burst of episodic activity, before onset of a stagnant-lid regime. However, either as the planet begins to age (decreasing internal heating as a proxy), or for higher values of surface temperatures and weaker lithospheres, the range of lithospheric strengths that episodic behavior occurs for increases, allowing for stable episodic-lid behavior as a long lived expression of tectonics. After $\sim 75 - 50\%$ of the original Q_0 is lost, the system becomes relatively insensitive to the effects of changing surface temperature on tectonic styles, and transitions driven by this mechanism are no longer possible. Additionally while the return to an active-lid mode of tectonics is possible, our models indicate that the surface temperature change would need to be far in excess of the surface temperature needed to transition to a stagnant-lid. This indicates that once a planet enters into a stagnant-lid regime, it is unlikely to transition back to a mobile-lid regime by a return to the original surface temperature. These results may suggest why a planet such as Venus may be operating in a stagnant-, or episodic-lid regime, and a planet such as the Earth is in an active-lid mode.

References: [1] Moresi, L. and Solomatov, V. (1998), JGR, 133, 669-682. [2] O'Neill, C. et al., (2007), EPSL 262, 552-562. [3] Lenardic et al. (2008), EPSL, 271, 34-42. [4] Landuyt & Bercovici (2009), EPSL, 277, 29-37. [5] Lenardic, A. and Crowley, J. W. (2012), The Astrophysical Journal, 755.2:132. [6] B.J. Foley, B. J., et al. (2012), EPSL 331, 281-290. [7] Zhong, S., et al. (2000), JGR, 105, 11063-11082. [8] Tan, E., et al. (2006), G3, 7, Q06001. [9] van Heck, H.J. and Tackley, P.J., (2008), GRL, 35, L19312. [10] Foley, B.J. and Becker, T.W., (2009), G3, 10, Q08001.

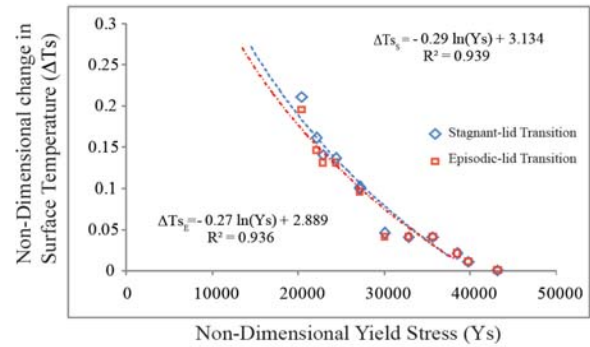


Figure 1: Regime transition diagram, plotting the change in surface temperature that results in convective regime change versus lithospheric yield strength. Results for both stagnant- (blue diamonds, and blue best fit natural log trend - ΔT_{s_s}) and episodic-lid transitions (red squares, and red best fit natural log trend - ΔT_{s_e}) are shown.

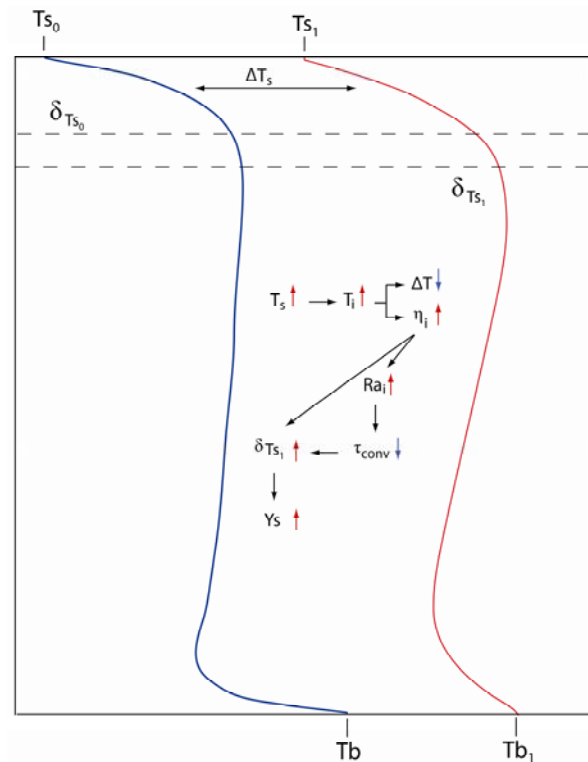


Figure 2: Increasing surface temperature schematic. Red arrows indicate quantities increase, blue arrows indicate a decrease. T_{s0} =original surface temperature, T_{s1} = new surface temperature, ΔT_s = change in surface temperature, δT_{s0} = original thermal boundary depth, δT_{s1} = new thermal boundary depth, T_b = original base temperature, T_{b1} = T_b + a function of ΔT_s , T_i = internal temperature