The Evolution of Terrestrial Planets: Multiple Tectonic Regimes and Diverging Geologic Histories. 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: Studies examining transitions in the mode of planetary tectonics (e.g. plate tectonics to a single plate planet) have generally fallen into two categories: 1) those interested in processes internal to the system, such as how variations in specific material and thermal parameters can effect the tectonic regime expressed [e.g. 1-5], and, more recently; 2) those interested in how the inherently non-linear behavior of the convecting system and the assumption of a set of initial conditions can control the tectonic regime expressed [6-8]. What is currently unclear is to what order the effects of parameter variation (e.g. yield stress and internal heating) in addition to initial starting states (e.g. stagnant- or mobile-lid) may have when both are evaluated concurrently. In this work, we use coupled 3D mantle convection and planetary tectonics simulations to explore the links between tectonic regimes as a function of the age, surface temperature, and initial starting state of a planet.

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 η=exp(-θT), where θ=EΔT, 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, ρ is the density, g is gravity, and z is the depth dependant term.

Numerical Methods: We explore the effect of variable surface temperature (T_s) and internal heating rates (Q) 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 [9-12]. The range of viscosity variation is 1e4 and is both temperature- and depth-dependent, Ra=1e5, and the modeling domain consists of a 32x32x32 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.

Results and Discussion: We've conducted a large suite of simulations exploring T_s, Q, and yield stress parameter space. Yield stresses are chosen such that the system begins in either a hot stagnant- (e.g. Q ~ 60 and near Earth valued yield stresses), or hot mobile-lid (e.g. Q ~ 60 and lower yield stresses). Free parameters (T_s and Q) are varied sequentially for a fixed value of yield stress, using the preceding simulation as the initial conditions for the following simulation. This is repeated until the system transitions from the initial tectonic state.

A mobile-lid planet with a high internal heating is susceptible to T_s induced transitions in tectonic styles. Systems that are conditionally stable may transition into a stagnant-lid through small changes in surface temperature (ΔT_s ~ 15 K). Transitions in tectonic modes cease as Q decreases by ~ 45%. Once the system becomes stagnant, a return to a mobile-lid by decreasing T_s to, or in excess of, the original value is not attainable. These findings suggest that transitions to a stagnant-lid via changes in surface temperatures alone must occur early in the planet's evolution and are a one way street.

However, a planet that is in a stagnant-lid for high degrees of internal heating may migrate through tectonic regimes as a function of decreasing internal heating rates, or ageing (Figure 1). Such ageing systems allow for the ability to transition into a mobile-lid from either an initial, or earlier T_s induced stagnant-lid state. These systems, with their complex thermal histories, may migrate through multiple stable mobile-lid states throughout their lifetimes.

Figure 2 illustrates the complexity in determining the tectonic mode for a system with a strong history dependence. Regions of multiple stable tectonic solutions exist for all but: (1) the starting state (hot systems: Q ~ 60); (2) the ending state (cold systems: Q ~ 0), and; (3) very strong lids (yield strengths > 105 MPa for our simple systems). As the system ages, mobile-lids may initiate from stronger stagnant-lids at lower values of internal heating (approaching Q ~ 10). At Q ≥ 60 the system exhibits two possible endmembers: a hot, strong stagnant-lid, and a hot, weaker strength mobile-lid. At Q ~ 0 the system exhibits again two possible endmembers: a cold, strong stagnant-lid, and a cold, weaker strength mobile-lid. H_w space increases for both older (low Q) and cooler surface temperature planets. Within the H_w region, there is an ability that large (overturn, impacts), or small perturbations (creation of large continents, changes in surface RMS, steady changes in solar luminosity) can allow a jump between regimes throughout the planet's lifetime in an almost quantum mechanics level of uncertainty. These results indicate that both the Earth and Venus likely initiated in a different tectonic state than is currently observed, and may offer an explanation for their divergent evolutions. An early conditionally stable mobile-lid Venus would have been highly susceptible to ΔT_s induced transitions, and an early stagnant-lid Earth may have migrated into a mobile-lid through decreasing internal heating rates.

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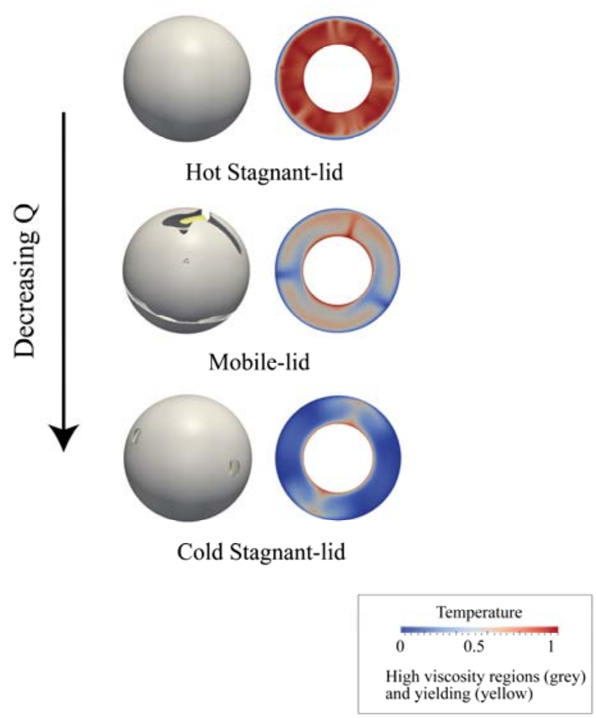

Figure 1: Effects of internal heating on tectonic regimes. Results shown are divided into a viscosity plot (grey shells are regions of high viscosity "plates" and yellow bands are regions of yielding) and thermal profiles from the CMB to surface.

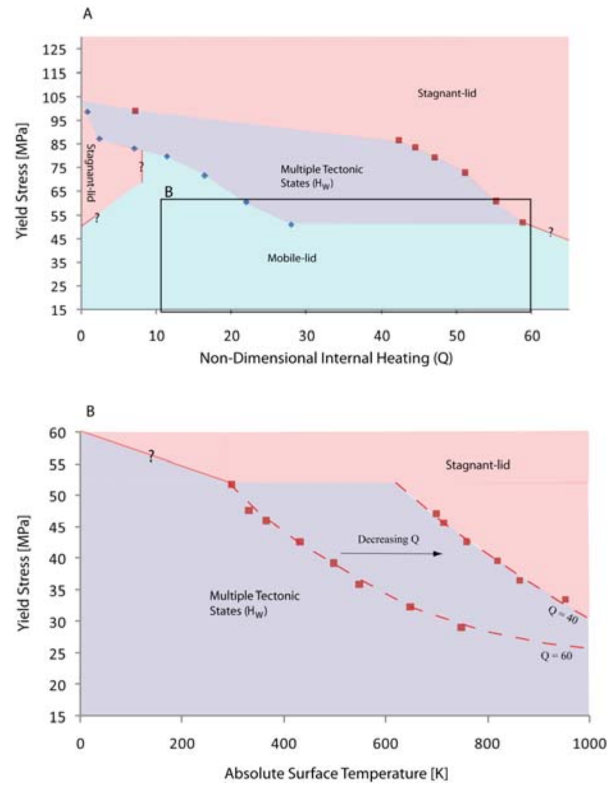

Figure 2ab: Diagrams showing regions of possible multiple stable tectonic regimes for a planet plotted for, A) Yield Stress and Internal Heating rates parameter space; and B) Yield Stress and absolute Surface Temperature parameter space in the mobile-lid regime of the Internal Heating parameter space (Box labeled B in A). Decreasing Q values are shown for the Q=60 and Q=45 case to illustrate the widening of H_w space as the planet ages. As Q decreases, larger amplitude surface temperature changes are required to initiate transitions into stagnant-lids. Red Squares indicate the transition into a stagnant-lid for the increasing parameter range (increasing values of internal heating or surface temperature), and blue squares signify transitions into stagnant-lids from decreasing parameter values (internal heating only).