Physics of Transitions in Global Tectonic Regimes: A New Paradigm for Venus?

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Introduction: The current and past tectonic states of Venus are hotly debated. Observations of Venus reveal a world resurfaced by vast volcanic plains, ~ 80%, which are thought to have been emplaced in the last 300 – 1000 Myr [1 – 3], perhaps 'catastrophically' [2, 3]. Currently, Venus shows no clear evidence of Earth-like plate tectonic activity, suggesting that the planet is either within a stagnant-, or episodic-lid regime [4–6], but may have exhibited some form of mobile-lid activity, perhaps locally, in the past [e.g., 7].

While recent attention has been paid to starting conditions of planetary bodies, and end member, steady state, stagnant-lid behaviors [e.g., 8 – 11] significantly less attention has been focused on the behavior of changing lid-states. Given growing evidence that planetary tectonic states can transition over time [e.g., 12 – 17], we address the thermal evolution of a planet that transitions out of a plate tectonic regime, and compare these to observations of Venus.

Changing Lid-States and Thermal Evolution: A transition from a long-lived (steady-state) mobile-lid to a stagnant-lid regime is shown in Figure 1 (see Figure 1 for a description of output and system parameters). The mobile-lid phase is dominated by organized convection, or large scale stable 'subduction' zones and spreading centers (Figure 2; A). The system in Figure 1 becomes unstable by an increase in an effective yield strength of < 8%, or conversely, a decrease of < 8 % in the effective convective stress from a conditionally stable mobile-lid initial condition. A change in the effective yield strength over time may be expected. One such mechanism is through the loss of pore fluids (specifically water) by surface warming, thus strengthening faults. The system response is ~ 6 overturn times before moving towards transitional (warming occurs from time 0, however). Here, the mobile-lid structure is disrupted by extreme oscillations in system activity. Episodic (transitional) phases are complex and highly dynamic. Temperatures increase from the shutdown of surface yielding. During a quiescent phase melt production decreases several orders of magnitude despite an increase in velocity and internal temperatures. Both melt production and temperature increases are offset from the initiation of surface immobility by 0.3 – 0.5 overturn times. As the system continues to warm, heat flux decreases to its minimum value of ~2.3 (which immediately proceeds remobilization events). These effects are due from a large-scale reorientation of the global convective aspect ratio, from one dominated by cold slabs sinking into the interior, to one lacking surface to interior interactions. The net result is a thickening global boundary layer that blocks decompression melt and convective heat flow.

As the system equilibrates to its new configuration, large plumes begin to develop (Figure 2; B1). As the plumes ascend, they destabilize the newly thickened thermal boundary layer, allowing for yielding to reinitiate (Figure 2; B2). The now warmer system yields much more energetically, increasing melt production and system velocity by three and two orders of magnitude, respectively (Figure 1; offset from yield initiation). Heat flux increases similarly. The previous mobile-lid organization is erased. As a consequence, individual episodic events tend to be disorganized and hemispheric to sub-hemispheric restricted, despite overall mobile-lid like Mobility rates. If multiple events occur, all hemispheres may be effected at different times. System and surface velocities tend to increase from the mobile-lid precursor by nearly an order of magnitude. Blocks of 'rafted' intact lithosphere may be preserved during rapid overturn events (Figure 2; B2). As the system progresses, overturns cease, and the system enters a stagnant-lid regime (Figures 1 and 2; C). Velocities and heat flow drop from thickening boundary layers. Melt increases with increasing temperature, as opposed to earlier mobile and episodic states where decompression melt dominates.

Timing and Implications: Once the system state becomes unstable (Figure 1), the total transition time is < 10 overturn times. This corresponds to time frames on the order of ~ two Gyr (assuming planet-like overturn timescales on the order 100 Myr). The signal of an individual overturn event (initiation to cessation) is on the order of 300 Myr, with initiation and cessation event time scales on the order of 100 (cessation) and 10 (initiation) Myr. Melt minima are offset from the shutdown of yielding (Figure 1) on the order of 100 Myr, corresponding with temperature inversions and heat flow changes. The implications for systems transitioning out of plate tectonics are: Punctuated and extreme oscillations in surface states, system velocities, and internal temperatures; significant and punctuated melt production, followed by a non-localized (diffuse) increase in melt production as a stagnant-lid state is entered; and finally, changes in global regimes tend to require Gyr time scales. These results suggest lid-state transitions are highly disruptive events, changing surface and internal characteristics significantly. For Venus, the implications are that global scale melt production and resurfacing are a natural consequence of lid-state evolution, without need of *ad hoc* resurfacing mechanisms which rely on a single governing lid-state. Interestingly, despite voluminous and punctuated hemispheric scale yielding and melting, original and intact lithosphere can be, and should be, expected to be preserved over Gyr time scales. This implies that a record of the thermal evolution of Venus may still be preserved discontinuously across the surface of the planet, simply waiting to be recognized.

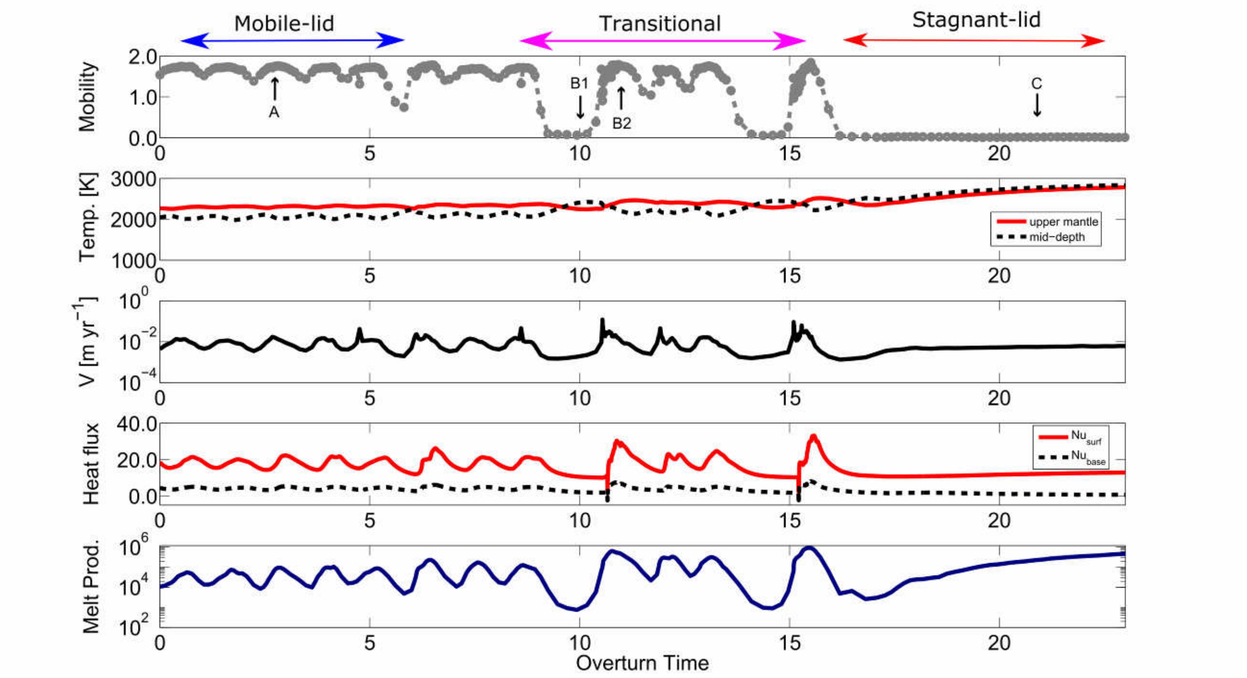

Figure 1: Results from finite element code CitcomS [18 – 20] showing a global tectonic regime evolution (for fixed parameters, below). Left to right: mobile- to episodic (transitional)- to stagnant-lids. Quantities with [ ] denote dimensional values, all other values are non-dimensional. Top panel, surface versus system velocities. Where Mobility ≥ 1 indicates a mobile-lid and a Mobility ≤ 0.1 indicates stagnant-lid. Second panel, temperatures in the upper mantle (red line) and mid-mantle (dashed black line). Third panel, bulk system velocity. Fourth panel, surface and basal heat flow. Fifth panel, melt production. The overturn time (x-axis, all panels) corresponds to the time a parcel takes (on average) to traverse the mantle. The Rayleigh number (definition for basally heated systems using the viscosity at the system base) is $6 \cdot 10^5$, with a temperature-dependant viscosity contrast of $6 \cdot 10^4$, an input heating rate of 60, a yield strength of $1.08 \cdot 10^5$ (increased from $1.0 \cdot 10^5$ at time 0), and the non-adiabatic temperature contrast is 3000 K. Overturn scales are useful when comparing low order Ra systems to planet-like values (e.g., Ra > 10^7).

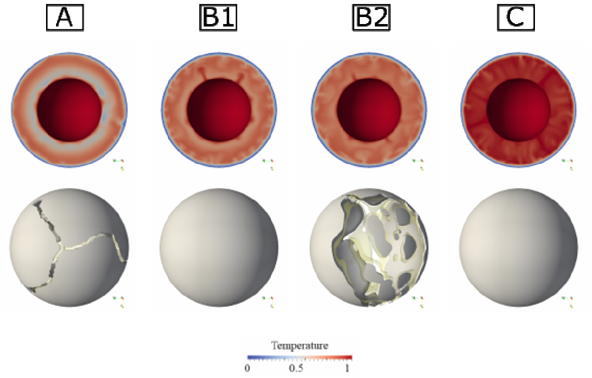

Figure 2: 3-dimensional spherical plots of a transition in regimes, indicated (letters) from Figure 1 – Mobility: (A) mobile, (B-1,2) episodic, and C) stagnant phases. The top row shows thermal profiles from the core mantle boundary to surface. The bottom row shows viscosity plots. Grey shells are regions of high viscosity “plates”, yellow bands are regions of active yielding.

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