From whiffs to pulses: links between tectonic evolution, outgassing, and atmospheric development

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Introduction: One of the most open and enduring questions in the sciences revolves around the apparent divergence in tectonic style and atmosphere between the sibling planets of Earth and Venus. Both planets are broadly similar in size and presumably bulk composition. As a result, they might be expected to have similar patterns of convection, heat loss, atmosphere development, and tectonics. However, while we understand the recent tectonic state of the Earth, the current and past tectonic states of Venus are unknown and vigorously debated.

The record of Venus is incomplete, however observations reveals vast volcanic plains, encompassing ~ 80% of the surface, which are thought to have been emplaced within the last Gyr [1 – 3], indicating relatively recent and prodigious melting events. Estimates for the recent rate of volcanism, inferred from the floors of large Venusian craters [4], range from ~0.5 to 4 km^3/yr [5, 6], or 1 to 20% of the rate of current Earth volcanism. Venus is currently blanketed by a thick 92 bar (~96.5% CO2) atmosphere with surface temperatures of ~740 K. Tectonically, the planet shows no clear evidence of plate tectonics as manifest on Earth, suggesting that it is either within a stagnant, episodic, or transitional regime [7 – 10]. These inferences, in addition to ^{40}Ar outgassing modeling studies [11 - 13] have lead to the suggestion of a poorly outgassed Venus (as compared to Earth). These results tacitly suggest that outgassing of the interior is not a primary driver of the atmosphere in recent geologic time. However, there are several lines of evidence that suggests Venus once did have a mobile lithosphere perhaps not dissimilar to Earth [7, 10, 14], and that the atmosphere may have altered to its current oppressive state geologically recently [15].

While attention has traditionally been paid to end member steady-state single plate stagnant lid behaviors [e.g., 16, 17], significantly less attention has been focused on the behavior of a change in tectonic regimes. Earth-based geochemical evidence and geodynamic models suggest that planets may transition between tectonic states over time [e.g., 18]. Observations for Venus further bolster this idea, suggesting a planet that evolved away from an Earth-like, mobile lithosphere toward a present-day stagnant-like tectonic state. This transition can occur though a change in the buoyancy force of convection, or from a change in frictional forcing operating on faults. Both changes are plausible consequences of time and both the planet's and Sun's evolution. The loss of pore fluids and water [19] can serve to strengthen faults [20], whereas increasing surface temperatures reduce the buoyancy forces that drives motion of the lithosphere [18, 21 – 22]. A planet may experience both effects simultaneously [10].

Here we explore the effects of a climate-driven change in lithospheric conditions on the evolution of mantle convection for Venus. From these transitioning cases, we further explore and evaluate the feedback between mantle outgassing and atmosphere generation.

Tectonic Evolution: Initial fault strength in the experiments is chosen to be consistent with a mobile lid (of which plate tectonics is an example). A transition in tectonic regimes is ushered in by as little as an 8% increase in fault strength, or a 5% increase in the surface temperature. Transitioning systems, from mobile to stagnant lid, are shown in Figure 1. Three cases are considered, two global yield strengths and one operating at higher internal temperatures.

Transitions in regimes are governed by regional and global scale instabilities, resulting in punctuated and extreme oscillations in mobility, internal temperatures, and magma production rates (and consequently volcanism). In the mobile regime, melt is generated by passive upwelling in spreading centers. In transitional states the majority of melting is plume generated and hemispheric to sub-hemispheric scale. Melt production increases by $\mathcal{O}(15)$ at peak activity and decreases by $\mathcal{O}(100)$ during inactivity (relative to base line mobile). Melt becomes spatially diffuse and increases as a stagnant lid state is entered (due to warming of the interior). Qualitatively, all perturbations (including to surface temperatures and internal temperatures) result in similar behaviors. The timing of the onset of oscillatory behaviors and subsequent surface immobility depends on the strength of the initial perturbation. Smaller, more subtle perturbations result in a longer transition period.

Tectonics, Melting, and Atmosphere: Melt production is linked to atmosphere generation through volcanism (here assumed to be extrusive melt generation) and volcanic degassing chemistry models which are surface pressure sensitive [26]. Our models are constrained to Earth-like interior compositions [27]. The initial atmosphere is assumed to be predominantly N_2 and CO_2 at 1 Bar surface pressure. We consider outgassing only endmembers. Atmospheric loss mechanisms are neglected.

Surface pressure and CO_2 increases approximately linearly in mobile lid phases due to quasi-steady outgassing rates (Figure 2). Overturn phases result in punctuated atmosphere generation events. During an individual overturn, atmosphere pressure increases by ~ 5 Bar in less than ~0.5 overturn times (< ~0.1 Gyr). As the system enters a stagnant lid, melt and atmosphere generation is subdued for $\mathcal{O}(5)$ overturn times (~ 1Gyr). Once the system equilibrates to its new thermal state, surface pressures increase at a greater rate.

All cases shown can generate a significant atmosphere: σ_y case 1 = 21.2, σ_y case 2 = 24.3, T_i case = 58 Bar; see Figure 1 for description (22%, 25%, 63% of Venus' atmosphere, respectively), and increase CO_2 concentrations by several orders of magnitude. Interestingly, despite a shorter transition period (and fewer overturns) for σ_y case 2 (relative to case 1) both σ_y cases show similar outgassed atmospheres. This is likely due to a longer period of stagnant lid activity for σ_y case 2. The T_i case generates substantial melt due to much higher internal temperatures (Figure 1), which offsets its somewhat more subdued transition.

Example speciation curves linked to melt production are shown in Figure 3. Under the assumption of an initial 1 Bar atmosphere (Figure 3A), H_2O dominates the outgassing species. SO_2 ranges from ~9% to 4% of the atmosphere. Each overturn produces pronounced shifts in relative abundances of outgassing species, indicating changing atmosphere concentrations with time.

Increasing the starting atmosphere pressure to 10 Bar (Figure 3B), CO_2 becomes the dominant outgassed species with significant reductions in both H_2O (~15%) and SO_2 (~2%) as compared to the 1 Bar case. The effects of overturn on atmospheric composition is reduced, and only slight changes in composition over time are reflected. Finally, assuming an initial thick 50 Bar atmosphere results in a strongly CO_2 dominated outgassed concentrations, low water concentrations, and minimal SO_2. Overturn phases have negligible effects on speciation, and the atmosphere is largely compositionally static.

Implications for Venus during (and after) transition: In a transition, Venus' surface/atmosphere would experience rapid and punctuated changes. Surface pressure may increase as much as 5 bar, with a similar increase in CO_2 concentrations over ~ 60 Myrs. With multiple overturn events, atmospheres of $\mathcal{O}(10)$ Bar are plausibly generated over sub Gyr time frames. Following this period of activity, outgassing would be negligible for ~ 1 Gyr, before melting resumes in the new stagnant state. Thick atmospheres, current reduced volcanism, and prodigious volcanism in the past Gyr, are all consistent with models of planet that is undergoing a transition in tectonics. Changing outgassing chemistry with time has strong implications for the development and constituent cloud species, including both H_2O and SO_2. Despite reduced levels, H_2O, if it exists within melt, is predicted to be outgassing today. These results have strong implications for putative habitable environments within the cloud deck of Venus.

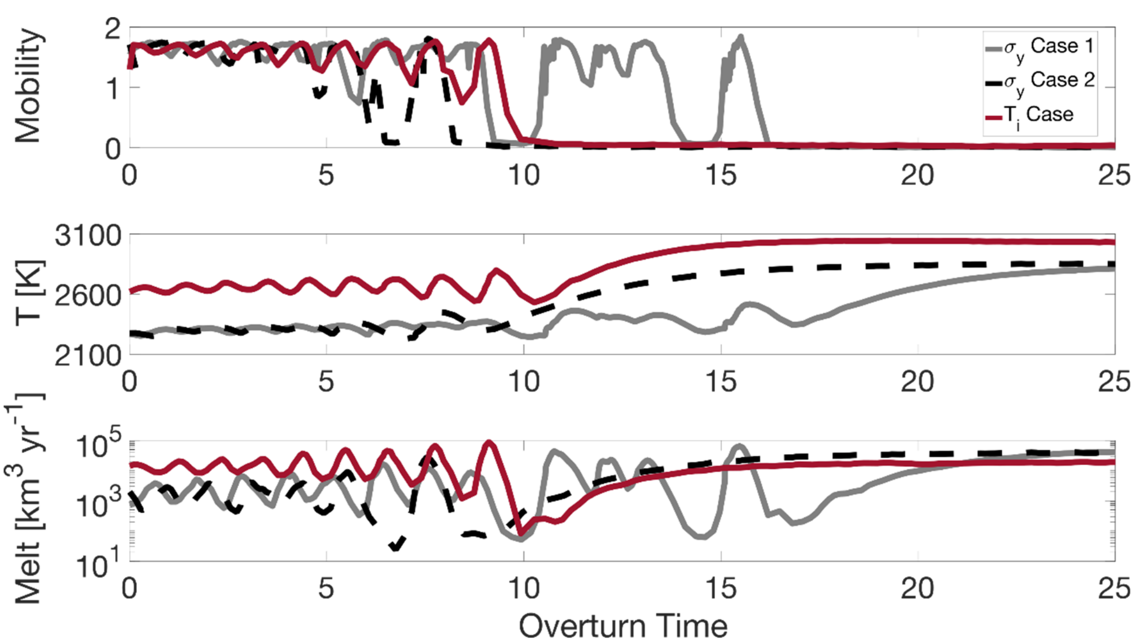

Figure 1: *Results from coupled thermal-tectonic three-dimensional numerical experiments using CitcomS [23 – 24]*

showing oscillatory tectonic states for a system transition from a mobileto stagnant lid. Panel (top): ratio of surface to internal velocity (Mobility). Mobility ≥ ~ 1 indicates horizontal motions and a mobile surface (mobile lid). Mobility ≤ 0.1 indicates surface immobility and quiescence (stagnant lid). Panel (middle): internal mantle temperatures. Panel (bottom): Melt production, which is calculated using established solidus and liquidus curves for peridotite [25]. The overturn time (x-axis, all panels) corresponds to the time a parcel takes (on average) to traverse the mantle (dimensionally, an overturn time is of $\mathcal{O}(100)$ Myr). Three different cases, two similar yield strengths (case 1 $\sigma_y = 1.08 \cdot 10^5$, case 2 $\sigma_y = 1.10 \cdot 10^5$, $T_{i0} = 2276$ K) and one different starting temperature (T_i case, $T_{i0} = 2620$ K, $\sigma_y = 4.25 \cdot 10^4$), are shown for illustrative purposes. The non-adiabatic temperature contrast is 3000 K for all cases

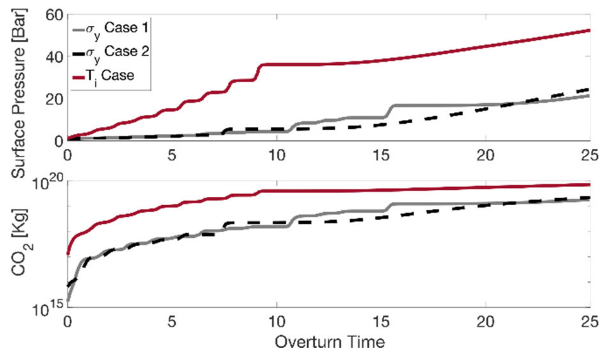

Figure 2: *Outgassed atmosphere from mantle melt production (Figure 1). Degassing products obtained from [26] and fixed to Bulk Silicate Earth [27]. Weathering and atmospheric removal processes are neglected.*

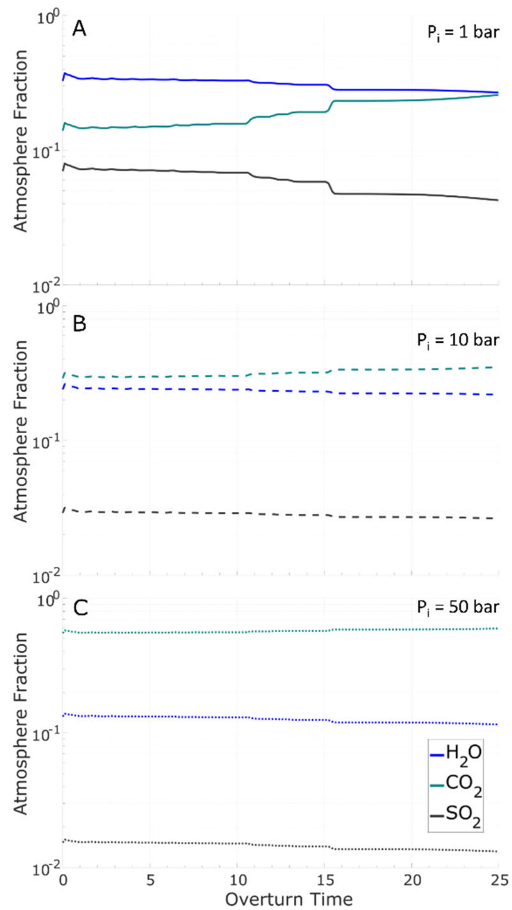

Figure 3: *Relative outgassed atmospheric fractions from outgassing of H_2O, CO_2, and SO_2 as a function of initial atmospheric pressures and overturn/melting history. Degassing products obtained from [26] and fixed to Bulk Silicate Earth [27]. Weathering and atmospheric removal processes are neglected.*

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