# Venus From the Interior to Surface: Atmospheric Evolution from Large-Scale Tectonic and Geodynamic Models.

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**Introduction:** Of all the first-order questions about the evolution of Venus, perhaps the most significant revolves around the apparent divergence in the atmosphere, surface, and tectonics between the sibling terrestrial planets of Venus and Earth. Both planets are of similar size and presumably bulk chemical composition, and at a first-order level, this might suggest that each planet would express similar patterns and styles of surface deformation, global tectonics, mantle convection, heat loss, and atmospheric evolution. However, while we know the current tectonics of the Earth, and ample data exists for its recent tectonic state (and in broad strokes its surface and atmospheric evolution), the current and past tectonic state as well as the atmospheric evolution of Venus are largely undetermined and hotly debated..

**The (Complex and Missing) Venusian Record:** Observations reveal volcanic plains that cover and obscure more than 80% of the planetary surface. Most of these plains' units are thought to have been emplaced within the last Gyr [1 – 3], which indicates recent and perhaps ongoing volcanism. 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] and are broadly similar to the rate of intraplate volcanism on the Earth.

Venus is suggested to be either within a stagnant single plate regime similar to Mars, or an episodic/transitional regime [6 – 9]. Traditionally, the observations of a non-plate tectonic Venus and models of $^{40}$Ar outgassing [10 – 12] derived from mantle melting, have been used to suggest that Venus is poorly outgassed when compared to Earth. These models have an important and tacit implication, that the outgassing of the interior is not, and cannot be, the primary driver of the atmosphere in recent geologic time, thus requiring the atmosphere to be 'ancient' and primordial [13]. Contrary to these assumptions, multiple lines of evidence directly suggest Venus once exhibited a more mobile lithosphere perhaps not dissimilar to Earth [7, 9, 14], and that the atmosphere may have altered to its current oppressive state geologically recently [15], suggesting that the interior plays a more prominent role in the development of the recent Venusian atmosphere.

Earth-based geochemical evidence and geodynamic models suggest that planets may transition between tectonic states over time [16]. Observations for Venus bolster this idea, suggesting a planet that evolved away from an Earth-like, mobile lithosphere toward a present-day stagnant-like tectonic state, driven by the coupled climate/interior (changing fault strength and surface temperatures) system.

**From Tectonics and Geodynamics to the Atmosphere and (Ultimately) Climate:** Here we explore a climate-driven change in lithospheric conditions on the evolution of mantle convection for Venus and couple these results to models of outgassing speciation [17] to drive the General Circulation Model (GCM) ROCKE-3D [18].

The initial fault strength is chosen to be consistent with a mobile lid state [9]. A transition in tectonic regimes is ushered in by as little as a 2% increase in fault strength (this can be caused due to loss of liquid water in the crust [19 – 20]), or a ~5% increase in the surface temperature. Initially, convection is in a mobile state. Due to the instability (either surface temperature or fault strength change) surface velocity begins to oscillate, with large decreases at ~1, 1.8, 2.4, 2.5, and 2.8 Gyr (scaled assuming Earth-like convective velocities); at ~1.8 and 2.8 Gyr, the lithosphere becomes fully stagnant for ~100 Myr. After ~3.8 Gyr the systems enters a final quiescent state (**Figure 1;** Case 1). Additional perturbations show similar behaviors (see **Figure 1** and caption for details).

Contrary to early thinking [e.g., 1-3] transitions in tectonic regimes are governed by both regional and global scale instabilities, resulting in oscillations in surface and core heat fluxes, surface and mantle convective velocities, and critically magma/volcanic production rates over Gyr time scales. Volcanism and yielding are almost exclusively non-global in extent and highly time dependent. At any time, portions of the surface may reflect vastly differing styles of convection, with some regions being highly active and other regions being sluggish to entirely inactive.

Initial atmospheric escape calculations suggest that hydrogen ($H_2$) from volcanism [17] is rapidly lost to space (**Figure 2**), with photochemical simulations yielding steady-state $H_2$ abundances on the order of 10 ppm. Other species are photochemically processed and removed from the atmosphere. $SO_2$ and $H_2S$ from the simulations react to form sulfate and sulfur aerosols that are subsequently rained out of the atmosphere, and CO is maintained at ~ppb levels because of fast oxidation by water vapor (via the hydroxyl radical, predominantly). The additional flux of carbon from large overturn events (**Figure 1**) into the atmosphere would lead to the geochemical sinks for $CO_2$ becoming overwhelmed faster, which could lead to more rapid climate transitions that separate a potentially temperate early Venus [25] from its present state.

The large-scale resurfacing events inferred from Venusian data is a natural consequence of the coupled tectonic-convective-climate evolution of a planet. We show that the mantle even into the relative recent Venusian past is a significant driver of atmospheric (and climatic) evolution, suggesting that Venus' surface, climate, atmosphere, and tectonics are dynamic and intimately and directly linked.

**References:** [1] McKinnon, W.B. et al., Venus II, pp.969-1014, Univ. of Ariz. Press, Tucson (1997); [2] Schaber, G.G. et al., Journal of Geophysical Research, 97, 13,257-13,301 (1992); [3] Strom et al. (1994) , 99, JGR-P; [4] Herrick and Rumpf (2011), JGR-P; [5] Stofan et al. (2005), Icarus 173; [6] Schubert et al. (1997), Venus II, Arizona Univ. Press; [7] Nimmo and McKenzie (1998), Annu. Rev. Earth Planet. Sci. 26; [8] Moresi and Solomatov (1998), JGR-P, 133; [9] Weller and Kiefer (2020), JGR-P, 125; [10] von Zahn et al. (1983), Composition of the Venus atmosphere; [11] Namiki and Solomon (1998). JGR, 103; [12] Kaula (1999), Icarus, 139; [13] Gillmann et al., Nat. Geo. (2020); [14] Kiefer (2013), LPSC 44, # 2541; [15] Way & Del Genio (2020), JGR, 125; [16] Weller & Lenardic (2018), Geo. Sci. Frontiers; [17] Gaillard, F. & Scaillet, B., Earth and Planetary Science Letters 403, 307–316; [18] Way, M.J. et al. The Astroph. J. Suppl. Ser. 231:12 (2017). [19] Grinspoon (1993), Nature 363; [20] Hubbert and Rubey (1959), GSA Bulletin 70; [21] Zhong, et al. (2000), JGR, 105; [22] Tan, E., et al. (2006), G3, 7, Q06001; [23] Hirschmann (2000), G3. [24] Arney et al. (2016), Astrobiology, 16(11); [25] Way, M.J. et al., Planetary Science Journal.,3, 92 (2022).

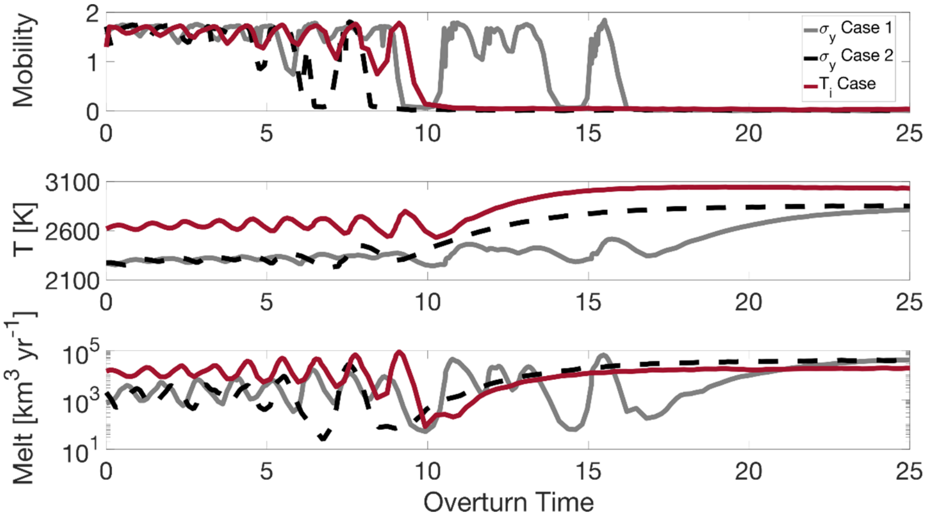

**Figure 1:** *Examples from coupled thermal-tectonic 3D numerical experiments (CitcomS) [21 – 22] a system transition from a mobile to stagnant lid. Panel (top): ratio of surface to internal velocity (Mobility). Mobility ≥ ~ 1 indicates a mobile lid. Mobility ≤ 0.1 indicates stagnant lid. Panel (middle): internal mantle temperatures (non-adiabatic temperature contrast is 3000 K). Panel (bottom): Melt production rate [23]. The overturn time (x-axis, all panels) corresponds to the time a parcel takes to traverse the mantle (dimensionally, an overturn time is of $\mathcal{O}$(100) Myr). Two yield strength changes (case 1 $\Delta\sigma_y$ = +8%, case 2 $\Delta\sigma_y$ = +10%) and one different temperature case ($T_i$ case, $\Delta T$ = +15%, $\sigma_y$ = -135%), are shown for illustrative purposes.*

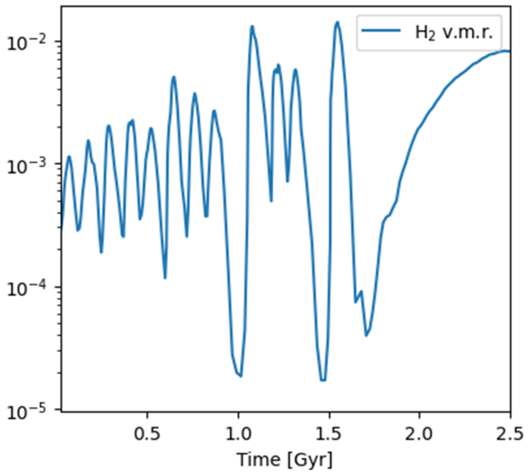

**Figure 2:** *When hydrogen outgassing is balanced by diffusion-limited escape to space, the steady-state mixing ratios approach percent-level amounts during periods of intense volcanic activity but is otherwise below 1 part per thousand. Photochemical simulations with Atmos [25] using average outgassing rates typically have $H_2$ volume mixing ratios 2-3 orders of magnitude lower.*