Atmospheric Evidence of Early Plate Tectonics on Venus.

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Introduction: Given comparable size and mass, Venus is often compared to Earth as its twin; however, Venus is strikingly different in terms of its atmosphere, surface, and tectonic state. Venus is shrouded by a thick oppressive 92-bar atmosphere comprised of ~96.5% CO_2, ~3% N_2, and trace gases, resulting in an extreme greenhouse climate with surface temperatures exceeding 700 K (e.g.,[1]). The surface of Venus consists of vast volcanic plains thought to have been emplaced within the last 300 Myr to 1 Gyr [2–5]. The surface record of Venus' evolution prior to ~ 1 Ga is notably absent, leading to significant uncertainties and debate regarding Venus' climate, tectonic, and atmospheric history [1, 6-10].

At present, Venus' surface shows no clear evidence of Earth-like plate tectonic activity [11, 12], supporting the idea that a non-plate tectonic Venus may have persisted for at least the last one billion years. However, there are suggestions in the geologic record that Venus may once have been more tectonically active. Western Ishtar Terra, an analogue to the Himalayas and Tibetan Plateau, may have formed through a convergent boundary [13–15]. Further, 'recent' subduction has been suggested beneath the margins of Artemis and Quetzalpetlatl coronae [16].

Understanding the current Venusian atmosphere may be key to unlocking Venus' tectonic and geologic past. *Venus' atmosphere is intimately linked to the planet's thermal-tectonic-geologic history and has likely preserved a record of Venus' evolution since antiquity*. Here we use numerical experiments of coupled thermal-tectonic-convection and outgassing atmospheres to determine atmospheric pressures and primary atmospheric compositions as a function of time and tectonic state for Venus.

Methods: We simulate the long-term thermal-chemical evolution of Venus using standard parametrized one-dimensional models of interior evolution [17]. For these models, interior heat that is generated is required to balance the heat lost from the surface:

$$V_m\left(H - \rho_m C_m \dot{T}_m\right) - \rho_m f_{pm} L_{pm} = A_c Q_c - A_s Q_s \quad (1)$$

where V_m is the mantle (subscript m) volume, C_m is the heat capacity, ρ_m is density, $\dot{T}_m$ is the time average change in the temperature, H is radiogenic heat production (here assumed to be initially chondritic), L_{pm} is the latent heat of melt, f_{pm} is the melt production, A is area and Q is heat loss from the core (subscript c) and from the surface (subscript s). A simplified version of equation (1) is used to track the evolution of a single layer core.

For the mantle, the Nusselt number (Nu) is given by a Nusselt-Rayleigh (Ra) relationship [e.g., 18, 19], and the viscosity (η) which is dependent on the temperature, pressure (p), water content (fH_2O) and melt fraction (φ), are defined as:

$$Nu \sim (Ra)^{\beta} \quad (2)$$

$$Ra = g\rho\alpha\Delta T d^3 / (\kappa\eta) \quad (3)$$

$$\eta(T_m, p, H_2O, \phi) = A_0 fH_2O \exp\left(\frac{E + pV}{RT_m} - \gamma\phi\right) \quad (4)$$

where α is the thermal expansivity, g is the Venusian surface gravity, κ is thermal diffusivity, d is the Venusian mantle thickness, A_0 and γ are empirical constants, R is the universal gas constant, and E and V are the activation energy and volume, respectively. The power term β is set to 0.33 (active lids) and 0.2 (stagnant lids) [18, 19]. We use standard solidus and liquidus relationships to track melting, modified to allow for the effects of water and depletion [20–22]. Melt production is linked to atmosphere generation through volcanic degassing chemistry models (which are surface pressure dependent) [23] and constrained to Earth-like interior compositions and fugacity [24].

Results: For early active lid regimes, outgassed atmospheres reach Earth-like pressures in less than 1 Myr, and Venus-like pressures soon thereafter at between ~12 and 100 Myrs (**Figure 1**). In contrast, stagnant lid regimes generate initially negligible rates of melting and outgassing, leading to pressures comparable to the initial atmosphere assumed of 10^{-3} Bar. In the stagnant lid regime, Earth-like pressures are achieved between ~14.5 and 400 Myrs (20 – 400x longer than active lids). Only the highest initial temperatures considered for the mantle (> 2850 K) and surface (> 500 K) generate atmospheric pressures that are comparable to current Venusian surface pressures.

The second most abundant chemical in the Venusian atmosphere, N_2, is inert, and may serve as a strong time integrated measure of outgassing for planetary bodies. Earth-like atmospheric N_2 masses are rapidly reached within ~10 to 70 Myrs, with Venus-like masses obtained at ~110 Myr for the hottest surface temperature cases (> 500 K), and by ~ 125 Myr for the nominal mantle temperature cases (2750 K) (**Figure 2**). The lowest surface (< 300 K) and internal temperature cases (< 2650 K) do not outgas sufficient N_2 to match current observations of Venus. In contrast, stagnant lid cases due to reduced early melting, and pressure effects on outgassed species, only reach Earth like values at > 1 Gyr for the highest surface temperatures, and no cases allow for sufficient outgassed N_2 to match Venusian observations.

Implications for Venus: The current mass of N_2 can be explained by outgassing of an early plate tectonic-like active lid regime. *Our results indicate that the outgassed atmosphere of stagnant lids under the best-case and perhaps unrealistic scenario of no - or extremely limited - atmospheric loss, underpredict and are unable to reproduce key Venusian data such as surface pressures, CO_2 (not shown), and N_2 abundances.*

For an early active lid Venus, these results require the atmosphere to have been largely emplaced within the first few 100 to 1000 Myrs, indicating that the current Venusian atmosphere has largely been preserved since antiquity. This indicates that an early 'runaway' active lid state could effectively lead to a great climate transition over a few 100 Myrs, suggesting that the atmosphere of Venus need not have been set primordially from a magma ocean (e.g., [8, 9]). Although a transition in tectonics is possible relatively recently [6, 7, 10], and such a transition can strongly effect the atmosphere at initial Earth-like surface pressures [25], it may not be solely required to explain critical aspects of the Venusian atmosphere. This has important implications for the stability of water and putative Venusian habitability.

References: [1] Bullock & Grinspoon, Icarus, 2001; [2] Schaber et al., JGR:P 1992; [3] Phillips et al., JGR-P 1992; [4] Strom, et al., JGR:P 1994; [5] McKinnon, 1997; [6] Way, et al. GRL 2016; [7] Weller & Kiefer, JGR-P 2020; [8] Gillmann et al., Nat. Geosci., 2020; [9] Gillmann & Tackley, JGR-P 2014; [10] Way & Del Genio, JGR-P, 2020; [11] Solomon et al., JGR-P 1992; [12] Schubert et al., 1997; [13] Kiefer & Hager, JGR-P 1991; [14] Kaula et al.,JGR-P, 1992; [15] Ivanov & Head, PSS 2008; [16] Davaille et al., Nat. Geosci. 2017; [17] Stevenson et al., Icarus 1983; [18] Schubert et al., Icarus, 1979; [19] Schubert et al., JGR-P 1980; [20] Sandu et al., JGR-P 2011; [21] Sandu & Kiefer, JGR-P 2012; [22] Maaløe, Mineral. Petrol. 2004; [23] Gaillard & Scaillet, EPSL, 2014; [24] McDonough and Sun, Chem. Geo. 1995; [25] Weller and Kiefer, 52nd LPSC, 1555, 2021.

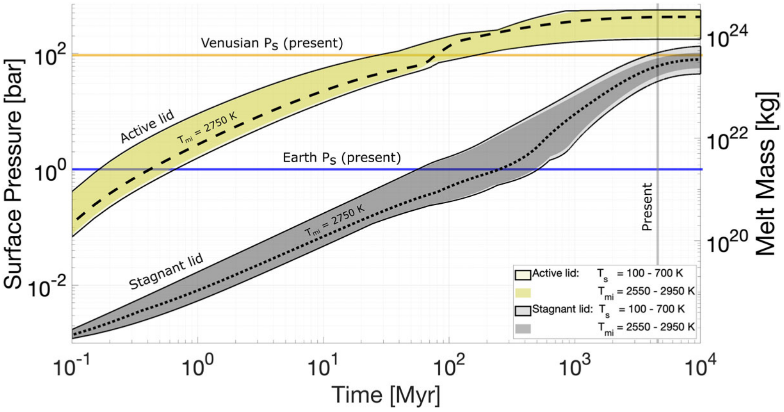

Figure 1: *Surface pressures and cumulative extrusive melt produced as a function of tectonic state, and both initial internal and surface temperatures. The yellow field indicates active lid convection results, the grey field indicates stagnant lid results. Central colored regions of both fields show ranges of mantle initial mantle temperatures (T_m), where lighter colors with solid outline indicate effects of surface temperatures (T_s).*

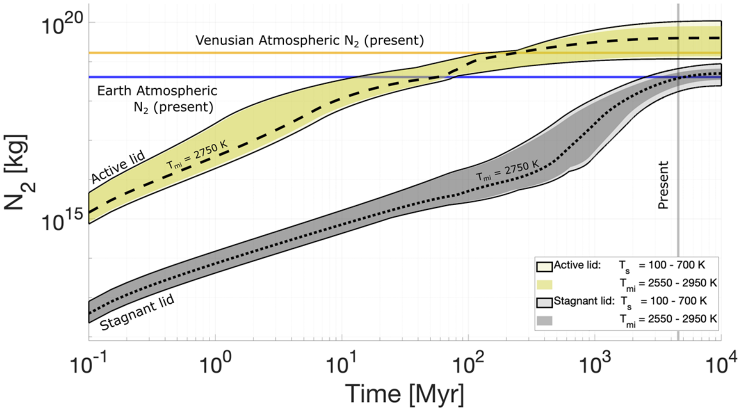

Figure 2*: Atmospheric reservoirs of chemical species as a function of tectonic state, as well as surface pressures and outgassing N_2. Description follows from Figure 1, with Venus (orange line) and Earth (blue line) atmospheric N_2 abundancies given for the present.*