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**VENUS' LIGHT SLAB HINDERS ITS DEVELOPMENT OF PLANETARY-SCALE
SUBDUCTION AND HABITABILITY**

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Abstract

Terrestrial planets Venus and Earth have similar sizes, masses, and bulk compositions, but only Earth developed planetary-scale plate tectonics. Plate tectonics generates weatherable fresh rocks and transfers surface carbon back to Earth's interior, which provides a long-term climate feedback, serving as a thermostat to keep Earth a habitable planet. Yet Venus shares a few common features with early Earth, such as stagnant-lid tectonics and the possible early development of a liquid ocean. Given all these similarities with early Earth, why would Venus fail to develop global-scale plate tectonics? In this study, we explore solutions to this problem by examining Venus' slab densities under hypothesized subduction-zone conditions. Our petrologic simulations show that eclogite facies may be reached at greater depths on Venus than on Earth, and Venus' slab densities are consistently lower than Earth's. We suggest that the lack of sufficient density contrast between the high-pressure metamorphosed slab and mantle rocks may have impeded self-sustaining subduction. Although plume-induced crustal downwelling exists on Venus, the dipping of Venus' crustal rocks to mantle depth fails to transition into subduction tectonics. As a consequence, the supply of fresh silicate rocks to the surface has been limited. This missing carbon sink eventually diverged the evolution of Venus' surface environment from that of Earth.

Introduction

Venus is regarded as a "twin planet" of Earth, having a slightly smaller radius (6052 km) and lower gravity ($g = 8.87 \text{ m/s}^2$)¹. Despite these similarities, Venus' CO₂-rich (> 90%) atmosphere ($4.8 \times 10^{20} \text{ kg}$)² is ~100 times denser than Earth's ($5.15 \times 10^{18} \text{ kg}$)³, resulting in a runaway greenhouse effect and extremely high surface temperature of 460 °C. The carbon budget of a planet's surface reservoirs is primarily governed by endogenic degassing and carbon sequestration processes. Magmatism and metamorphism in tectonically active regions release carbon into the atmosphere^{4,5,6}, whereas newly formed silicate rocks are subject to weathering that sequesters atmospheric CO₂. The size of this carbon sink depends primarily on the supply rate of fresh silicate reactants or the weathering reaction kinetics^{7,8}. Both the input and output fluxes are strongly associated with the tectonic regime of a planet.

The twin planets Venus and Earth show contrasting tectonic characteristics. Planetary-scale subduction does not seem to operate on Venus, and therefore it is widely accepted that Venus is in a stagnant-lid regime⁹. A similar tectonic pattern is inferred to have been prevalent on early Earth, before primitive plate tectonics emerged^{10,11}. The origin of plate tectonics on Earth is an ongoing fundamental debate in geosciences^{12,13}. Some researchers suggest that plume upwelling and magma loading broke the lithosphere and initiated proto-subduction^{14,15}. This lithospheric damage accumulated and formed plate boundaries¹⁶; self-sustaining subduction further drove plate tectonics on Earth¹⁷. Plumed-induced subduction sites are also identified around corona structures on Venus^{18,19}. The question comes as to why the local subduction failed to trigger plate tectonics on Venus.

Here, we explore the mechanisms for the lack of large-scale subduction on Venus from a petrologic perspective and further discuss the consequences. As a crustal slab sinks into the mantle, the increasing pressure produces dense metamorphic assemblages, which, if denser than mantle rocks, would drag the slab further into the mantle and promote plate convergence. Such a process dating back to as early as the Neoarchean on Earth²⁰ is favored in cold geothermal conditions^{16,21}. In nucleating and sustaining subduction, water plays a vital role as hydration weakens shear zones in the lithosphere²², and lubricates the slab interface in the subduction zone²³. Modern Venus clearly meets neither necessity. However, studies suggest that early Venus might have had a similar liquid ocean and surface temperature to the Archean Earth²⁴. Assuming such a favorable environment existed, we explore whether metamorphism on Venus would have resulted in dense slabs. Specifically, we perform forward phase equilibria simulation to model the mineral assemblages, densities of Venus' slabs along typical subduction-zone geotherms. From the modeling results, we discuss how the crustal compositions and densities diverge the tectonic and environmental evolutions of Venus from that of Earth.

Modeling slab densities and tectonic development

There are three measured bulk compositions of Venus' crust from the USSR landing probes in the 1980s: Venera 13²⁵, Venera 14²⁵ and Vega 2²⁶. These data were acquired by X-Ray Fluorescence (XRF), and reflect a broadly basaltic crust of Venus. Light elements (e.g., Mg) had large uncertainties. In particular, Na concentrations were unavailable from XRF but were estimated using K, Mg and Fe oxides concentration^{25,26}. The Venus' crust appears to have higher Al contents and lower contents of divalent cations than that of early Earth²⁷. Isostatic compensation models are not able to identify major heterogeneity within Venus' crust by fitting topography and gravity data²⁸; without further constraints, we use these three data points to represent the crustal composition of Venus. We model the equilibrium phase relations in the pressure-temperature (P-T) ranges of 0.5-3.5 GPa, 300-900 °C (Fig. 1, S1), using similar approaches reported in ref. 27 (See Methods). The predicted mineral assemblages and mineral compositions enable us to estimate the rock densities. We then test the sensitivity of our modeled slab densities to Na, Mg concentrations to account for the large uncertainties associated with Venus' crust.

The pressure-temperature (P-T) phase diagrams for the three Venus samples are topologically alike—the eclogite-facies assemblages consisting of dense minerals (garnet and omphacite/diopside) are only stable at $> \sim 1.5$ GPa (conservatively ~ 60 km) and > 530 °C (green-shaded in Fig. 1, S1). These Venus' eclogite fields are smaller than those of the Archean-Proterozoic terrestrial samples²⁷. The similarities of the moments of inertia and the average densities adjusted to the sizes between Venus and Earth allows us to presume that the mantle density of Venus approaches the Preliminary Reference Earth Model (PREM), and accordingly, these two planets have similar internal and thermal structures²⁹. Similar to ref. 27, we consider two representative geotherms on Venus—11.3 °C/km (warm) and 8.1 °C/km (cold). The densities of Venus' slabs are generally lower than Earth's Proterozoic slabs along both geotherms, by up to 0.1-0.2 g/cm³ (Fig. 2a, b). Venus slabs' higher Al contents result in more abundant low-density minerals like chlorite and lower proportions of high-density minerals garnet and pyroxene. The depth that reaches eclogite-facies condition is 5-10 km greater on Venus than Earth. The Venus' slab densities are about 3.2 g/cm³ at 55 km along a warm geotherm (Fig. 2a), or 70 km along a cold geotherm (Fig. 2b). At such depths, the Proterozoic Earth's

slab densities²⁷ exceed 3.3 g/cm³ and approach mantle density (~3.35 g/cm³). Along both geotherms, the Venus' slab densities shoot up and reach ~3.4 g/cm³ in the next 10-15 km due to eclogitization (Fig. 2b, S3a), remaining at 3.35-3.55 g/cm³ at greater depths (Fig. S3). The slab densities exceed that of the upper mantle at ~65 km along the warm geotherm (Fig. S3a), and ~75 km along the cold geotherm (Fig. 2b). The density of metamorphosed Venera 14 approaches that of the Paleoproterozoic high-MgO basalt on Earth²⁷. We note that the Venera 14 composition is distinctively Mg-poor, and the effect of compositional variations on the slab density is discussed below.

We now explore how the uncertainties in concentrations may influence the equilibrium mineral assemblages and densities. To do this, we first propagate the analytical uncertainties and calculate the density and its likely range by assuming that the three XRF measurements sampled a uniform Venus' crust (Table S2; see Method). As an example, at 525 °C along the warm geotherm, the distribution of the sampled densities peak at 3.07 g/cm³, with 1 σ standard deviation of ± 0.03 g/cm³ (Fig. 2a inset), so the density of Venus' average slab is significantly lower than Earth's. We then run phase equilibrium simulations and slab density calculations at 650 °C with $\pm 30\%$ variations in bulk rock Na and Mg contents (Fig. S5, S6, Fig. 2c, d). The Na content, or the Na/Ca ratio, of the crustal protolith, influences the relative stabilities of glaucophane, pyroxene, and garnet³⁰ (Fig. S5). However, the density variation due to the uncertainty associated with the Na content is minor (< 0.05 g/cm³, Fig. 2c). Mg and Fe²⁺ substitute in mafic minerals, such as garnet and pyroxene. Mg-endmembers are less dense, resulting in lower rock density. Mg numbers (Mg# = molar Mg/[Mg + Fe]) of the three samples range from 0.62 to 0.72. The densities drop significantly as the Mg contents increase, by up to 0.1 g/cm³ along the cold geotherm and 0.15 g/cm³ along warm geotherm, respectively (Fig. 2d). If the bulk Mg# of Venera 14 were comparable to the others, it would have a similarly low density. Venus has been resurfaced in the past ~500 Myr^{31,32}, and therefore its surface rocks represent a relatively modern crust. In the early history of a planet, the melting of a hotter mantle would have produced crustal rocks with higher Mg contents³³. The Mg-rich protolith composition results

in less dense metamorphic rocks, especially along a warm geotherm (Fig. 2d). Thereby, our modeling results could be regarded as an upper limit for the slab density on early Venus.

On Earth, prototype subduction submerged a slab to the mantle depth, triggered self-sustaining subduction, and initiated plate tectonics^{10,12,34}. High-pressure metamorphism creates a dense slab and facilitates slab subduction to greater depths³⁵ (Fig. 3b) where the cold core of the subducting slab further contributes negative thermal buoyancy³⁶ (Fig. 3c). The negative buoyancy induced by phase transformation might play a particularly important role in the Archean when the basaltic crust was thicker than present³⁷. The recycling of slab gives rise to new crustal materials generated at convergent and divergent boundaries (Fig. 3c). On Venus, the modeled slab's densities are consistently lower than Earth's by $> 0.1 \text{ g/cm}^3$, and bulk density averaged from shallow depths to 80 km is $3.18\text{-}3.30 \text{ g/cm}^3$ along the warm geotherm, or $3.14\text{-}3.25 \text{ g/cm}^3$ along the cold geotherm (Fig. S4). The average densities of slabs hardly exceed the mantle density ($\sim 3.35 \text{ g/cm}^3$). At these depths, the mantle lithospheres of the subsiding and overriding plates are of similar temperatures (Fig. 3b), so the negative thermal buoyancy of slab is minor. Given that 80 km is the overestimation for crustal thickness³⁸ and the depth of incipient subduction¹⁸, spontaneous subduction is unlikely triggered by local and temporal dipping of crust (Fig. 3b). The root of thickened orogen could also delaminate (Fig. 3c), an alternative recycling pathway that might prevail in the Archean. The eclogitized lower crust still needs to be dense enough to introduce gravitational instability³⁹, which is unlikely archived on Venus, either. We speculate that light slabs diverged Venus' tectonic regime from Earth in the early stage (Fig. 3d). The difference in tectonic regime eventually leads to contrasting surface carbon budget, environments, and habitability on these two planets.

Earth and Venus' environmental evolution

Both Earth and Venus have considerable amounts of magmatic CO_2 degassing (Tmol/yr), despite of their different tectonic regimes. Combining with the metamorphic decarbonation⁴⁰ and clay formation by reversed weathering⁴¹, the total decarbonation rate is 4 to 29 Tmol/yr on Earth. As for Venus, the long-term

average volcanic eruption rate is $\sim 0.37 \text{ km}^3/\text{yr}^{32}$; given $> 4 \text{ wt. \% CO}_2^{42}$ and a density $\sim 2.5 \text{ g/cm}^3$ of the basaltic magma, this endogenic carbon flux on Venus reaches 1 Tmol/yr , half-to-one orders of magnitude smaller than on Earth.

Silicate weathering is the primary mechanism of CO_2 removal from the atmosphere^{43,44}, of which the rate is limited by either the reaction kinetics or the supply rate of reactants^{7,8}. The difference in the tectonic regime on Earth (plate tectonics) and Venus (stagnant-lid) lead to a large discrepancy in the tectonic resurfacing rate. On Earth, the large amount of fresh rock produced at active plate boundaries ($\sim 30 \text{ km}^3/\text{yr}$, mostly from mid-ocean ridges⁴⁵ and arcs⁴⁶) and a proper land fraction result in a high CO_2 -consumption rate of $16 \text{ to } 27 \text{ Tmol/yr}^{47,48}$. The subsequent carbonate deposition ($\sim 3.6 \text{ Tmol/yr}^{49}$), followed by subduction or crustal delamination, provides a path for recycling carbonate back to the mantle and establishes a planetary thermostat⁵⁰ (Fig. 3c). When both the surface temperature and weathering rate are primarily controlled by the greenhouse gas content in the atmosphere, negative feedback and thus planetary thermostat could be established⁵⁰. By contrast, subduction on Venus came to a premature end (Fig. 3b, d). Without sufficient new crustal material generated at active plate boundaries, fresh silicate rocks are mainly produced by plume-related volcanism at a rate of $\sim 0.37 \text{ km}^3/\text{yr}^{32}$, about $\sim 1/100$ the rate of that in Earth ($\sim 30 \text{ km}^3/\text{yr}$). Thus, weathering is ‘supply limited’⁵¹, is less sensitive to temperature, and proceeds at a slow rate on Venus⁵².

Efficient resurfacing on Earth, which is brought by active plate tectonics, sustains a long-term negative feedback that prevents Earth’s carbon from being accumulated in the atmosphere or being stored entirely in the lithosphere. Even in a supposedly sluggish tectonic regime in the Neoproterozoic⁵³, resurfacing brought by active plate tectonics would still be enough to balance carbon degassing⁵⁴. On the stagnant-lid Venus the CO_2 consumption is unlikely to catch up with the endogenic carbon emission, resulting in a long-term CO_2 accumulation in Venus’ atmosphere, runaway greenhouse climate, and eventual ocean evaporation

within 1 b.y.⁵⁵. In return, the warming surface and lithosphere, together with an anhydrous crust, prevented self-sustaining subduction and locked Venus in a stagnant-lid regime.

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Author Contributions

X.C. initiated the idea, J.C. performed simulation, and J.C. and X.C. wrote the first manuscript. All authors contributed to data interpretation and manuscript writing.

Competing Interests

The authors declare no competing interests.

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Figure Captions

Figure 1. P-T phase diagram in the range 300-650 °C, 0.5-2.5 GPa calculated for Vega 2 composition (Table S2). The phase diagram is labeled with mineral assemblages and stability boundaries of important phases (garnet, pyroxene, amphiboles). The cold (8.1 °C/km) and warm (11.3 °C/km) geotherm are shown as yellow dashed lines. The eclogite-facies assemblages are highlighted in light green. The phase diagrams for the other two compositions are presented in Fig. S1, and the phase relations at higher pressures and temperatures are presented in Figure S2.

Figure 2. (a,b) The Earth²⁷ (blue) and Venus (red) slab densities along warm and cold geotherms from 300 to 650 °C. The inset diagram in Figure 2a shows the statistical distribution of Venus' slab density at 525 °C along warm geotherm (see Method). The slab densities at higher pressures and temperatures are shown in Fig. S3 and the bulk densities of slabs are shown in Fig. S4. **(c,d)** The slab densities as functions of the variations of bulk Mg and Na concentrations at 650 °C. The phase diagrams are presented in Figures S5 and S6.

Figure 3. Schematic cartoons illustrating the tectonic evolutions on Earth and Venus, and their diverging carbon cycles. (a) Plume upwelling breaks the lithosphere. (b) Incipient slab dipping on Venus and Earth; eclogitization might trigger self-sustaining subduction. (c, d) Difference in Earth and Venus tectonic and environmental evolution as results of different slab densities and subduction self-sustainabilities (see text for discussions).

METHODS

Through thermodynamic and mass balance equations, the minerals + fluid equilibria and their compositions are calculable for a fixed rock bulk composition (X) at specific pressure (P)-temperature (T) conditions. The equilibrium phase diagrams, also known as “pseudosection”, depict the phase relations and outline the areas of stable phase assemblages in P-T, T-X and P-X spaces. In this study, we use the bulk compositions of Venus’ crust to plot P-T, P- X_{Mg} , P- X_{Na} equilibrium phase diagrams. Assuming that the metamorphism in a hypothesized subduction zone reaches equilibrium, the plotted P-T equilibrium phase diagrams indicate the slabs’ mineral assemblages along subduction geotherms. The P- X_{Mg} , P- X_{Na} diagrams reflect the influences of Na, Mg concentration variances on the mineral assemblages and their compositions. The equilibrium phase diagrams are calculated by using THERMOCALC version 3.33 (<https://hpxeosandthermocalc.org/>), thermodynamic dataset of ds55 (ref. 56) and compatible activity models (Table S3). To estimate the bulk density of a slab averaged from shallow to mantle depths, we model the phase equilibria in a larger pressure and temperature range (up to 3.5 GPa, 900 °C; Fig. S2). We do not include silicate melts due to a lack of compatible activity models. Incipient melting would lower the bulk density and strength of a slab, impeding slab subduction. The effect of partial melting is further discussed in Supplementary Information.

We use the NCKFMASHTO (Na_2O – CaO – K_2O – FeO – MgO – Al_2O_3 – SiO_2 – H_2O – TiO_2 – O_2) model system. The crust compositions of Venus are represented by three available X-ray fluorescence data (Table S1,2) from USSR landing probes Venera 13²⁵, Venera 14²⁵ and Vega 2²⁶. The Venera 13 composition is an alkaline basalt likely consisting of weathered olivine leucitite, nephelinite. Venera 14 and Vega 2 are both weathered N-MORB-like basaltic tholeiite. We assume that ocean existed on the early Venus like the Earth, the basaltic crust could have been hydrated. Progressive dehydration reactions during metamorphism keeps H_2O saturation. The crustal $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ ratios are mainly controlled by the mantle redox condition and partial melting process. Assuming similar settings of the early Earth and Venus, we use the same ratio

as the early Earth ($\text{Fe}^{3+}/(\text{Fe}^{2+} + \text{Fe}^{3+}) = 0.1$ in mole, ref. 27). The three Venus data all contain a fair amount of sulfur, which might reflect anhydrite (CaSO_4) or sulfate-bearing scapolite⁵⁷, the products of chemical weathering by an extreme atmospheric SO_2 content. If Venus had liquid ocean at its early stage, the sulfur content would not have been as significant. Thus, we ignore the S contents in our model. We do not remove corresponding CaO from the bulk composition because sulfur weathering does not introduce additional CaO. The MnO contents are low, have large uncertainties, and barely affect the phase relations, so we omit MnO in the model system. The other elements' mass percentage are transferred into mole fraction for the calculation.

Phase equilibria modeling predicts quantitative mineral proportions and compositions. The rock densities (ρ) are calculated on basis of the information from phase relations and the minerals' thermoelastic parameters, using a similar method as ref. 58:

$$\rho = \sum_{i=1}^n \rho_i v_i$$

where

v_i is the volume fraction of a mineral (mode), provided by the phase equilibria modeling results;

ρ_i is the density of a mineral, calculated using:

$$\rho_i = \frac{\sum_{j=1}^m M_j x_j}{\sum_{j=1}^m V_j x_j}$$

where

M_i is the molar weight of an endmember, calculated from its formula;

x_j is the mole fractionation of one end member, provided by the phase equilibria modeling results;

V_j is the molar volume of an endmember, calculated from the equation of state in ref. 56:

$$V_j = V_T \left(1 - \frac{4P}{K_T + 4P} \right)^{1/4}$$

where

V_T is the molar volume at 1bar, T (Kelvin in unit), $V_T = V_{1,298}[1 + \alpha_0(T - 298) - 2\alpha_0\alpha_1(\sqrt{T} - \sqrt{298})]$, in which α_0, α_1 : the thermal expansion parameter;

K_T : the end-member's bulk modulus at T (Kelvin in unit), $K_T = K_{298}(1 - 1.5 \times 10^{-4}(T - 298))$, in which K_{298} is the bulk modulus at 298 Kelvin, and $V_{1,298}$ is the molar volume at 1 bar, 298 Kelvin (standard condition).

In addition to phase relations corresponding to these three individual bulk compositions, we propagate the uncertainties of concentrations, and calculate Venus' slab density and its standard deviation, to explore how likely the slab density of Venus overlap those of Earth. This exercise is time consuming, so we only calculate at 525 °C, along the warm geotherm, where the calculated slab densities of two Venus bulk compositions (Venera 13 and 14) overlap the densities of Earth's Proterozoic slabs (Fig. 2a). The assumption is that these three XRF data all represent one hypothetical uniform crustal composition of Venus. The means and standard variations of Venus' crustal bulk compositions are shown in Tables S1 and S2. At each step, we randomly sample one element's abundance within its range (Gibbs sampler), model the phase relations using the new bulk composition, and calculate the density of the assemblage. We perform 300 such sampling (Table S4), and then fit the series of calculated densities into a normal distribution for the mean and standard deviation of the density estimate.

Figures

Figure 1

P-T phase diagram in the range 300-650 °C, 0.5-2.5 GPa calculated for Vega 2 composition (Table S2). The phase diagram is labeled with mineral assemblages and stability boundaries of important phases (garnet, pyroxene, amphiboles). The cold (8.1 °C/km) and warm (11.3 °C/km) geotherm are shown as yellow

dashed lines. The eclogite-facies assemblages are highlighted in light green. The phase diagrams for the other two compositions are presented in Fig. S1, and the phase relations at higher pressures and temperatures are presented in Figure S2.

Figure 2

(a,b) The Earth²⁷ (blue) and Venus (red) slab densities along warm and cold geotherms from 300 to 650 K. The inset diagram in Figure 2a shows the statistical distribution of Venus' slab density at 525 K along warm geotherm (see Method). The slab densities at higher pressures and temperatures are shown in Fig. S3 and the bulk densities of slabs are shown in Fig. S4. **(c,d)** The slab densities as functions of the variations of bulk Mg and Na concentrations at 650 K. The phase diagrams are presented in Figures S5 and S6.

Figure 3

Skematic cartoons illustrating the tectonic evolutions on Earth and Venus, and their diverging carbon cycles. (a) Plume upwelling breaks the lithosphere. (b) Incipient slab dipping on Venus and Earth; eclogitization might trigger self-sustaining subduction. (c, d) Difference in Earth and Venus tectonic and environmental evolution as results of different slab densities and subduction self-sustainabilities (see text for discussions).

Supplementary Files

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- [SupplementaryTable4.xlsx](#)
- [Supplementary.docx](#)