DEGASSING, DECARBONATION, AND DEHYDRATION: INVESTIGATING THE LIKELIHOOD OF A HABITABLE ERA ON VENUS.

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Introduction: Understanding the divergent evolution of Earth and Venus is one of the primary motivations to explore Venus. Recent climate models suggest habitable conditions may have been possible until 1 Ga,[1] but how a habitable era would fit into Venus' atmospheric evolution has yet to be investigated. We use overall mass balance constraints atmospheric evolution to determine areas of parameter space that enable a habitable era to have occurred on Venus.

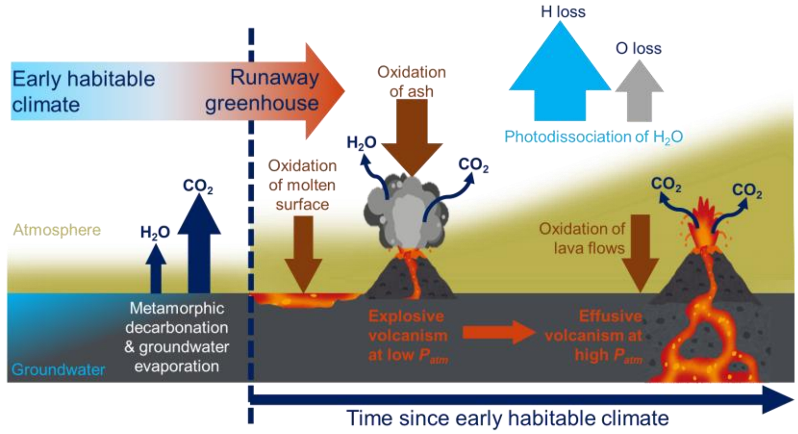

Figure 1. Schematic illustration of our new Venus atmospheric evolution model. We use a wide range of free parameters to identify areas of parameter space that maximize the likelihood of a habitable era on Venus.

If an early habitable climate existed on Venus, it required an atmosphere thinner than the present-day 93 bar, CO_2-dominated atmosphere.[1] There are 2 options for the source of the bulk of the CO_2 atmosphere observed today: 1) *Volcanic degassing* - delivery of melt to Venus' crust and surface brings magmatic volatiles which are released into the atmosphere. 2) *Metamorphic decarbonation* - carbonates formed during the early habitable period are heated by a combination of burial and increasing surface temperatures until the point of thermal decomposition, releasing CO_2 back into the atmosphere.[2]

In either case, CO_2 is not the only volatile introduced into the atmosphere. Unless Venus' mantle is desiccated/volatile depleted, water vapor will also degas during volcanic eruptions.[3] For metamorphic decarbonation, some surface liquid water is required for initial carbonate formation and to maintain habitable conditions.[1] This implies the presence of groundwater in the early Venusian crust to prevent infiltration of surface water into the deep crust. This groundwater would evaporate during a runaway greenhouse, injecting water vapor into Venus' atmosphere alongside CO_2 from metamorphic decarbonation.

There are 2 main constraints on the likelihood of a habitable era on Venus: 1) Venus' atmosphere is dry, with an upper limit of 100ppm water vapor[4], so if large volumes of water were added to the atmosphere they must since have been removed by loss to space (hydrous minerals are not stable on the present-day surface[5,6]). 2) Venus' atmosphere is oxygen-poor, with a maximum of 50ppm O_2,[7] so O_2 left behind by H_2O photolysis and H escape must be compensated by loss of O to space and other oxygen sinks, e.g. oxidation of Fe^{2+} to Fe^{3+} in the crust.

Model Description: There are many unknowns in Venus' atmospheric history, including the source of atmospheric CO_2 (early magma ocean degassing, metamorphic decarbonation, or volcanic degassing), the ratio of intrusive to extrusive volcanism on Venus, and the planet's crustal production history.[8] For the first time, we model the evolution of Venus' atmosphere starting at the end of a habitable era, and take a Monte-Carlo approach to find combinations of parameters most consistent with both a habitable period on Venus and present-day constraints on atmospheric O_2 and H_2O.

We assume that Venus' habitable era predates ~0.7 Ga.[9] Dehydration and decarbonation of the habitable era crust are assumed to occur instantaneously, so the atmosphere begins with some initial CO_2 and H_2O. Initial CO_2 depends on the fraction of present-day atmospheric CO_2 derived from volcanic degassing (a free parameter). Initial H_2O depends on the groundwater inventory during the habitable era, which is calculated using a simple basalt crust permeability model,[10] given an uncompressed basalt porosity and habitable-era crustal heat flow.

Chemical analyses of rocks at the Venera 14 and VEGA 2 landing sites resemble tholeiitic basalts,[11] so we consider a range of melt volatile concentrations based on those observed in terrestrial mid ocean ridge basalts. We use VolcGasses[12] to calculate pressure dependent H_2O and CO_2 solubility in basaltic melt throughout the model. A time-dependent crustal production rate is calculated for each model using estimates of present-day eruption rates, and the chosen intrusive:extrusive ratio and melt CO_2 concentration are adjusted so that the final mass of atmospheric CO_2 matches Venus' present-day atmosphere.

For volatile loss from Venus' atmosphere, we assume a uniformly mixed atmosphere and complete photodissociation of H_2O by UV photons. Thermosphere temperature varies between model runs from 200-4000K.

At high H_2O mixing ratios, H escape is limited by incoming solar XUV radiation. At lower H_2O mixing ratios and XUV flux, H escape is limited by diffusion of H through the surrounding atmosphere.[13,14] Oxygen is lost from the atmosphere by early hydrodynamic escape and on-going non-thermal escape.[15] We assume negligible CO_2 loss to space.

O_2 can also be lost through oxidation of volcanic products. Hematite is stable under present-day Venus conditions,[5,6] and exposed basaltic olivine and glasses should oxidise under present-day Venus conditions within weeks to months.[5,6] Oxidation of lava flows may only be in a thin surface rind[15], but explosive basaltic volcanism on Earth produces fine-grained ash and scoria[16] which could fully oxidize more quickly. A potential predictor of whether explosive volcanism can occur is the gas:magma ratio,[17] calculated at each timestep using degassed CO_2 and H_2O volumes. When the gas:magma ratio exceeds 3:1, we assume complete oxidation of the basaltic volcanic products.

Preliminary Results: The parameters that most strongly influence the likelihood of a habitable era on Venus are melt volatile concentrations, fraction of volcanically derived CO_2 in the present-day atmosphere, and when the habitable era ended. High combined melt H_2O and CO_2 concentrations favor explosive volcanism, the products of which are a very effective O_2 sink and can erase the O_2 signature of large habitable era H_2O inventories. However, high melt H_2O contributes more H_2O (and therefore O_2) to the atmosphere which can accumulate rapidly once the ash sink is no longer active. Additionally, high melt CO_2 is anticorrelated with the total erupted volume of lavas, the main O_2 sink at high atmospheric pressures. Similarly, a low volcanically derived CO_2 fraction limits the total volume of volcanic products available to oxidize. An early end to the habitable era maximizes the total possible loss of H and O from both groundwater and volcanism. A late end to the habitable era precludes high melt H_2O and large habitable era water inventories because there is not enough time for H or O escape to meet both the present-day H_2O and O_2 concentrations in Venus' atmosphere.

Our preliminary modelling results outline two sets of parameter combinations that maximize the likelihood of a habitable era on Venus: 1) *Early habitable Venus ($\gtrsim$2.5 Ga)* – favored by low melt H_2O concentrations, habitable groundwater inventory <0.2 terrestrial oceans (TO), low total crustal production, an intrusive:extrusive volcanism ratio of ~10:1, and a small contribution of volcanic CO_2 to Venus' present-day atmosphere. 2) *Late habitable Venus ($\lesssim$2.5 Ga)* – favored by melt H_2O concentrations >0.5 wt%, habitable groundwater inventory <0.1 TO, high crustal production rates, and melt CO_2 concentrations <200ppm.

Although much of Venus' geologic record may have been lost to resurfacing, the crustal production histories of terrestrial planets can be recorded by ^{40}Ar, Xe, and ^{4}He.[8] Noble gas measurements by DAVINCI+[18] would help better constrain timing and total volume of crust produced on Venus, which would refine both our priors on fraction of post-habitable era volcanic CO_2 and crust production model. Whether high melt H_2O is typical of Venusian volcanism can be tested using spectral measurements of the surface by VERITAS or DAVINCI+ to determine the abundance of low Fe, high SiO_2 rocks.[18,19] This measurement alone would be powerful in distinguishing between the likelihood of an earlier vs. later habitable era on Venus. Our results also have implications reaching beyond our Solar System - constraining the likelihood of a Venusian habitable period may be useful for determining whether young exo-Venuses are good targets in the hunt for habitable worlds.

Future Work: During a runaway greenhouse, water-rich atmospheres can generate surface temperatures exceeding the basalt solidus.[20] Oxidation of FeO in a surface melt layer could provide an important O_2 sink. This sink is most important for habitable era scenarios with large groundwater inventories (>0.1 TO). Catastrophic resurfacing events may also be important for CO_2 and H_2O outgassing and provide a late O_2 sink in the form of FeO in melt exposed to the atmosphere. We will consider the effects of both these processes in future models.

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