**CONSTRAINTS ON EARLY VENUSIAN HABITABILITY FROM ATMOSPHERIC OXYGEN.** A. O. Warren[1] and E. S. Kite[1], [1]Department of Geophysical Sciences, University of Chicago (aowarren@uchicago.edu).

**Introduction:** As the only other Earth-size planet in our Solar System, Venus offers an opportunity to look at the potential fates of Earth-size planets closer to their stars. Where Earth has liquid water oceans, Venus has a desiccated 93 bar CO2 atmosphere and a mean surface temperature of 740 K. Much of Venus' geologic history is obscured by resurfacing event 0.3 to 1 Gyr ago, and we have few measurements of what geology there is on the present-day surface, so the planet's early history remains an enormous open question. Although there are many evolutionary scenarios for Venus where the condensation of liquid water at the surface is not possible, depending on the details of Venus' magma ocean period[1] and cloud radiative effects[2], models of both Venus' climate under different conditions,[3,4] and models of Venus' coupled interior-atmosphere evolution[5] have demonstrated that surface conditions on Venus could have been habitable as recently as 700 Ma. With several new Venus missions on the horizon for the next decade, it is important to use existing data to identify the most useful measurements we can make of the surface and atmosphere to figure out whether our most similar Solar System neighbor was ever habitable.

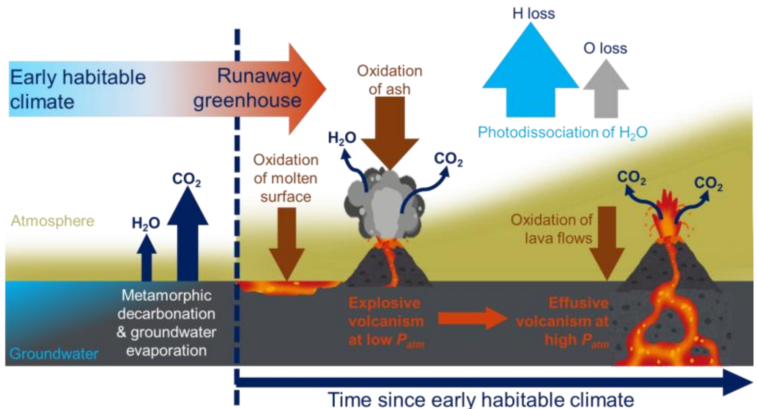


**Figure 1**. Sketch of our Venus atmospheric evolution model in the case where runaway greenhouse surface melting occurs.

If Venus had a habitable era with surface liquid water, this should have left an imprint on Venus' present-day atmosphere. Whether the habitable era ended through an increase in the Sun's luminosity, or a buildup of atmospheric $CO_2$ through volcanism, the liquid water present during the habitable era would have eventually evaporated and entered the atmosphere. Photodissociation of this water and loss of H would have then led to accumulation of O in the atmosphere.[6] There are therefore 2 main constraints on the likelihood of a habitable era on Venus: 1) Venus' atmosphere is dry, with <100ppm $H_2O$[7], so if large volumes of water were added to the atmosphere they must have been removed by loss to space because hydrous minerals are not stable on the present-day surface[8,9]. 2) Venus' atmosphere is oxygen-poor, with <50ppm $O_2$,[10] so any $O_2$ accumulation must have been compensated by O loss to space and other oxygen sinks, e.g. oxidation of $Fe^{2+}$ to $Fe^{3+}$ in the crust.

Here, we present a time-dependent, mass-balance model of Venus' evolving atmospheric composition starting from the end of a hypothetical habitable era when Venus had surface liquid water. We use this model to identify regions of parameter space where the $H_2O$ (and therefore $O_2$) added to Venus' atmosphere by the evaporation of habitable era surface liquid water and subsequent volcanic outgassing can be removed by non-thermal O escape, and oxidation of basaltic materials including ash, lava flows, and melt generated during a possible runaway greenhouse phase.

**Model Description:** Our model (shown in Fig. 1) includes 4 key processes: 1) Initial atmospheric inputs of $H_2O$ and $CO_2$ leftover from the earlier part of Venus' evolution and released into the atmosphere at the end of the habitable era. The habitable era $H_2O$ inventory represents the total atmosphere, surface, and subsurface water present on a temperate early Venus. 2) Escape of H and O to space based on equations for XUV and diffusion limited H escape,[11] dragging of O by rapidly escaping H,[6] and upper limits on nonthermal O escape over time calculated in previous work.[12] assuming a uniformly mixed atmosphere and complete photodissociation of $H_2O$ by UV photons. We assume negligible $CO_2$ loss to space.[13] 3) Volcanic $H_2O$ and $CO_2$ inputs, calculated using the open source code VolcGases[14], using melt volatile concentrations based on the range observed in Mid Ocean Ridge basalts. 4) Oxidation of volcanically derived minerals on Venus' surface. We assume that melts on Venus (and therefore also the planet's surface) resemble tholeiitic basalts based on chemical analyses of

**Table 1**. List of the 6 parameters varied in our model.

| | Description | Range | Units |
|---|---|---|---|
| $t_{start}$ | End of habitable era | 1.5 - 4 | Ga |
| $z_{H2O,0}$ | Initial water inventory | 100 – 1000 | m GEL |
| $m_{H2O}$ | Melt $H_2O$ concentration | 0.001 - 1 | wt. % |
| $m_{CO2}$ | Melt $CO_2$ concentration | 300 – 2000 | ppm |
| $f_{volc}$ | Fraction of atmospheric $CO_2$ from post-habitable era degassing | 0.1 - 1 | - |
| $f_{ext}$ | Fraction of melt reaching the surface | 0.1 - 1 | - |

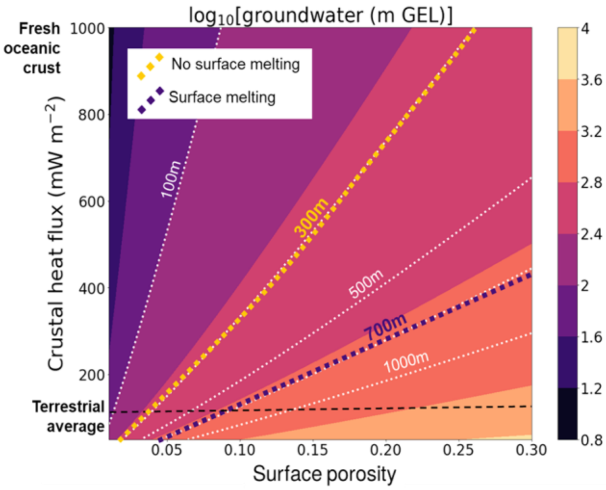


**Figure 2**. Maximum habitable era water inventories compared to the equivalent depth of water that can be stored in the subsurface.

rocks at the Venera 14 and VEGA 2 landing sites[15] and calculate the extent of melting using alphaMELTs.[16,17]

In our model, we vary 6 key parameters (Table 1) to find which values are most likely to be compatible with Venus' present day atmospheric $O_2$ and $H_2O$ abundances. We also investigate the impact of oxidation of FeO in a surface melt layer as an additional O sink in our models. This is because water-rich atmospheres can generate surface temperatures exceeding the basalt solidus,[18] and Venus may have had such a water-rich atmosphere at the end of a hypothetical habitable era, for example if habitability ended with a runaway greenhouse state.

**Results & Discussion:** Our results show that when surface melting during a runaway greenhouse does not occur, the maximum water inventory on early Venus is 300m GEL. When surface melting does occur, this increases to 700m GEL, provided that the habitable era ended around 4 Ga. Therefore, oxidation of a basaltic melt layer caused by a runaway greenhouse may be an important $O_2$ sink on rocky planets closer to their stars.

Whether or not runaway greenhouse surface melting occurs, habitable eras as recent as 1.5 Ga are consistent with Venus' present day atmospheric composition, in agreement with previous work,[3,5] provided that the habitable era water inventory was ≤100m GEL. However, habitable eras ending at 4 Ga are much more likely to meet modern atmospheric $O_2$ constraints and even with larger habitable era water inventories. This is because nonthermal O escape is faster earlier in Venus' history[12,13] and more time is available for O to be removed by lava flows.

Other parameters that favor evolution after a hypothetical habitable era matching modern $O_2$ measurements are average melt volatile concentrations <0.2wt% $H_2O$ and <500ppm $CO_2$. Average melts wetter than 0.2wt% $H_2O$ continue to add $H_2O$, and therefore $O_2$, throughout the model, which increases the total amount of $O_2$ that needs to be lost. Lower melt $CO_2$ concentrations, high crustal production rates, and >50% of melts reaching the surface as lava flows increase the total amount of oxidizable material delivered to Venus' surface as the planet builds up its modern 90 bar $CO_2$ atmosphere and make a given model run more likely to get rid of all $O_2$ built up after the end of the habitable era.

Even though a small exchangeable reservoir (<100m GEL) can sustain the clouds required to keep surface temperatures on Venus habitable until 0.7 Ga[3], comparing our maximum habitable era water inventories to a simple pore closure model[19] for a range of crustal heat fluxes and porosities shows that even when runaway greenhouse surface melting occurs, the maximum 500m GEL water inventory on early Venus may have been able to drain into the crust, which should be considered in future early Venus climate modelling.

Upcoming Venus missions offer an opportunity to test the predictions made by this model. Firstly, the crustal production histories of terrestrial planets can be recorded by $^{40}Ar$, Xe, and $^{4}He$.[8] Noble gas measurements by DAVINCI+[20] will help better constrain timing and total volume of crust produced on Venus. Whether high melt $H_2O$ is typical of Venusian volcanism can also be tested using spectral measurements of the surface by VERITAS or DAVINCI+ to determine the abundance of low Fe, high $SiO_2$ rocks.[20,21]

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