

INVESTIGATING THE GEOCHEMICAL CONDITIONS ON THE VENUSIAN SURFACE DURING THE POSSIBLE CLIMATE TRANSITION. H. T. White^{1,2,3} and V. F. Chevrier², ¹College of Earth, Ocean, and Atmospheric Sciences, Oregon State University (whitehas@oregonstate.edu), ²Arkansas Center for Space and Planetary Sciences, Univ. of Arkansas (vchevrie@uark.edu), ³Lunar and Planetary Institute (USRA), Houston, TX.

Introduction: While Venus remains similar to Earth in size and mass, present-day Venus is inhospitable with atmospheric pressures over 90 bars and an average surface temperature of 470°C [1]. With the discovery of a global resurfacing event hundreds of millions of years ago [2], Venus' geologic history has become a significant area of study. Several evolutionary simulations, including general circulation models [3] and coupled interior-atmosphere models [4], have demonstrated a possible habitable Venus model with stable liquid water, temperate climate, and plate tectonics. Here, we present a thermodynamic model of Venus' geochemical evolution during this transition period to find mineral and gas markers indicative of earlier atmospheric conditions. Modeling the marks left by this transition can help to constrain past habitability and understand Venus' evolution.

Methods: To simulate the thermodynamic evolution of Venusian geochemistry, we used the software *Geochemist's Workbench*®. The *React* module was used to simulate the equilibrium parageneses between various crust models, a primitive ocean, and the atmosphere. Mineralogical data was collected from the *Thermo.com.v8.r6+* database, which is based on the Debye-Hückel theory [5] for the calculation of activity coefficients of electrolyte solutions.

The initial fluid composition i.e., the primitive ocean uses standard concentrations of seawater on Earth with an average temperature of 25°C [6]. This model provides an approximation of a stable liquid water ocean during a clement period. The typical concentration of chlorine was dedicated as the charge balance and maintained the neutrality of the fluid while minerals precipitated. Aluminum was added to the composition to satisfy the plagioclase feldspar present in nearly all basaltic rocks. 7.5 µg/kg of aluminum was added to this solution, which is the average concentration of aluminum in seawater due to dissolution of clay minerals [7]. 3 mg/kg of iron was added for the iron oxides present in igneous crusts [8].

Three crustal compositions were tested in our models: tholeiitic basalt, granodiorite, and anorthosite. Tholeiitic basalt was used as due to a direct observation of oxide composition from Venera 13 [9]. Granitoids and Anorthosite were chosen as they are both interpretations of the composition of Venusian Tessera from VITRIS emissivity of Alpha Regio [10]. Granodiorite oxide compositions [11] and major oxides

from gabbroic anorthosite [12] were used to model granitoids and anorthosite respectively.

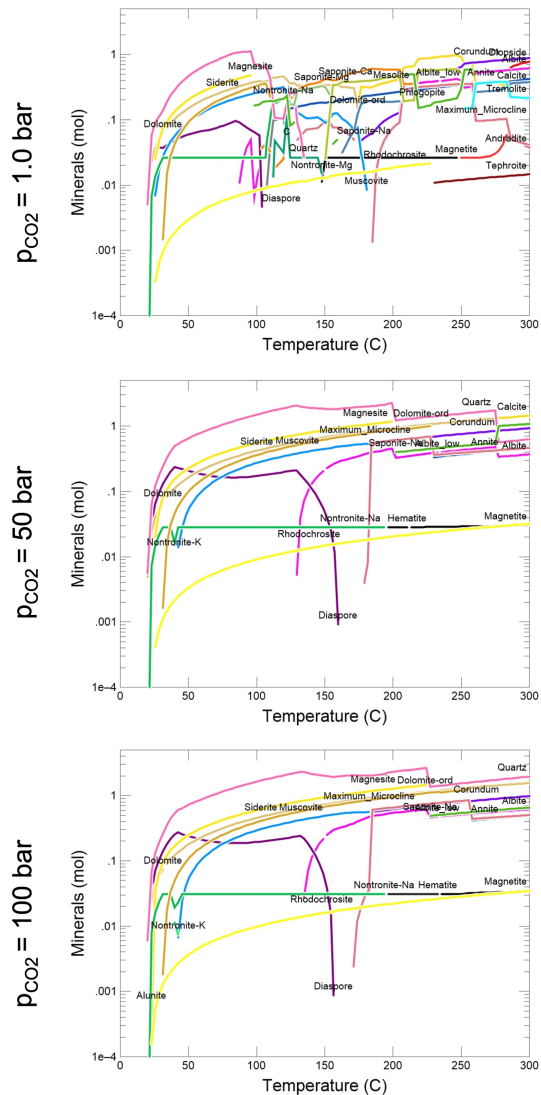


Fig.1 Mineral evolution as a function of temperature for a tholeiitic basalt crust under oxidizing conditions ($pE = 13.05$)

This model focuses on the evolution of the parageneses with temperature varying from 20°C to 300°C to represent the transition from a habitable environment to the present-day hothouse. Three different partial pressures of CO_2 were used; one modeling the present-day atmosphere (100 bars) and the other two modeling earlier potential atmospheres (1 and 50 bars). The pressure of CO_2 is fixed in each simulation for an open system. The redox conditions were also tested using the electron activity in aqueous solutions

(pE). Oxidizing conditions of $pE = 13.05$ (Fe^{2+}/Fe^{3+} redox couple) and reducing conditions of $pE = 2.407$ (S/H_2S redox couple) [13] were tested, but not maintained by the system. With varying pE and pH, the model calculated the most stable phases of minerals and gases and recalculates the pH and pE at each step.

Results: The mineral evolution for the tholeiitic basalt crust in oxidizing conditions at each partial pressure of CO_2 are presented in Fig 1. Higher pressure conditions show fewer mineral assemblages and different temperature ranges. At 1 bar of CO_2 , nesosilicates diopside (clinopyroxene), andradite (grossular garnet), and tephroite (manganese olivine) are markers of high temperature and low pressure. Mesolite (zeolite-group) appears at medium temperatures and low pressures only. High aluminum oxide content in tholeiitic crust forces silica from quartz into mesolite, which is not seen in higher pressures or in other crust models at low pressure. Tremolite (amphibole-group), which has been suggested as a possible water-carrier remnant on the surface of Venus [14], is a marker of high temperature and low pressure.

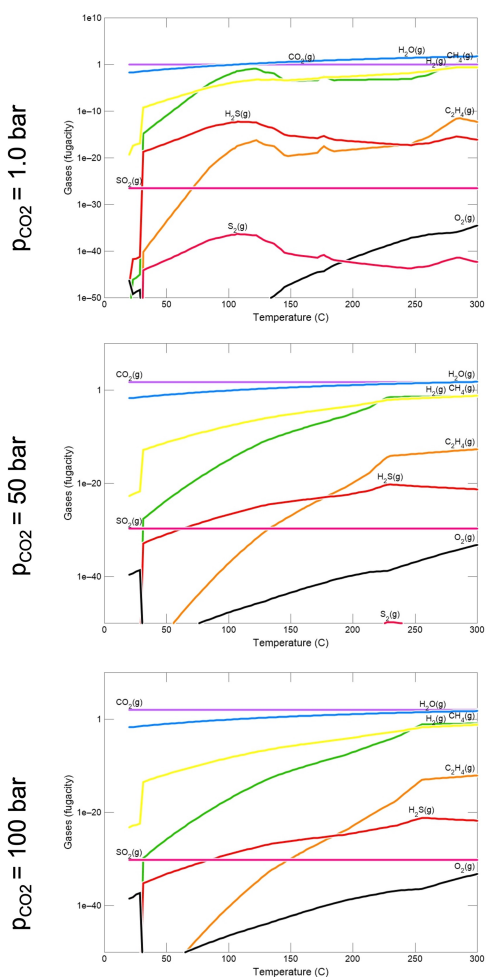


Fig 2. Fugacity under different partial pressures of CO_2

A variety of smectites appear at lower pressures, with nontronite appearing more at lower temperatures and saponites at higher temperatures. Above 50 bars of CO_2 , only sodium smectites survive along with a very small amount of potassium nontronite at low temperature. Phyllosilicates also occur at every temperature and pressure level, with muscovite at lower temperatures and annite at higher. Carbonates, iron oxides, aluminum oxides, and feldspars show similar parageneses between the three partial pressures. Feldspars and iron oxides are present in high temperatures, with feldspars being more abundant.

Fig. 2 presents the gas fugacities in equilibrium with the mineral assemblages at each partial pressure of CO_2 . The fugacities of SO_2 and CO_2 are held constant for oxidizing conditions. At 1 bar of CO_2 , the gas fugacities generally increase to about $100^\circ C$, above which they remain generally constant. At higher CO_2 pressures, the fugacities of C_2H_4 , CH_4 , H_2 , H_2S , and S_2 are lower compared to those found at 1 bar but increase over the whole range of temperatures to maximum levels at $300^\circ C$, comparable to results at 1 bar of CO_2 . O_2 fugacity is slightly higher at and above 50 bars.

Discussion and Conclusion: The results of this model show mineral and gas phases that are markers of specific conditions during Venus' possible transition from habitable to inhabitable. The presence of tremolite and mesolite are notable signs of a past climate with lower pressures. This model does not reach current Venus temperatures, consequently, some minerals (e.g., hydroxides) may destabilize in modern Venus conditions. However, the existence of many of these phases today could indicate a past clement environment with stable liquid water.

Acknowledgments: This work was supported by the Summer Undergraduate Program for Planetary Research and the LPI Cooperative Agreement.

References: [1] Fegley Jr. B. and Treiman A. H. (1992) *Venus and Mars: Atm., Ionospheres, and Solar Wind Interactions*, 66, 7-71. [2] Kreslavsky M. A., et al. (2015), *Icarus*, 250, 438-450. [3] Way M. J. and Del Genio A. D. (2020) *JGR: Planets*, 125. [4] Krissansen-Totton J. et al. (2021) *The Planet. Sci. J.*, 2(216). [5] Debye P. and Hückel E. (1923) *Phys. Z.*, 24, 185-206. [6] Alanezi K. and Hilal N. (2007) *Desalination*, 204, 385-402. [7] Hydes D. J. (1977), *Nature*, 268, 136-137. [8] Armstrong F. A. J. (1957) *J. mar. biol. Ass. U.K.*, 36, 509-517. [9] Dyar M. D. et al. (2021) *Icarus*, 358(114139). [10] Gilmore M. S. et al. (2015) *Icarus*, 254, 350-361. [11] Słaby E. et al. (2007), *Mineralogy and Petrology*, 89, 1-29. [12] Mukherjee D. et al. (2005) *J. of Asian Earth Sci.*, 25, 77-94. [13] Chevrier V. F. and Morrison M. (2020) *JGR: Planets*, 126. [14] Johnson N. M. and Fegley Jr. B. (2000) *Icarus*, 146, 301-306.