

# Modeling surface rock alteration on Venus

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## 1. Introduction

Venus is predominantly composed of volcanic plains, typically located within 1 to 3 km of planetary datum and spanning up to several thousand km in length [1]. Morphological features [2] and the limited *in situ* chemical analyses of Venus' surface materials by the Venera and Vega landers [3,4] suggest that the volcanic plains and rises are composed of basaltic rock [5]. In contrast, tesserae highlands terrain covers only 8% of the surface of Venus but appears to be the stratigraphically oldest material [2]. While the composition of the elevated tesserae remains unknown, surface optical emission through the atmospheric spectral windows at  $\sim 1 \mu\text{m}$  suggests relatively high-albedo materials [6] such as felsic rocks, fine-grained materials, scattering on rough surfaces, condensation and/or accumulation of solids from the atmosphere, and gas-solid chemical reactions [7]. Further, an unexplained phenomenon is the occurrence of apparently secondary solids with elevated dielectric and/or magnetic properties at altitudes above  $\sim 2\text{-}5$  km. A variety of processes and materials have been proposed including sulfides, chalcogenides, and metals [8].

Material on the surface of Venus at the level of modal planetary radius is exposed to temperatures of 740 K ( $\sim 470^\circ\text{C}$ ) and pressures of 95.6 bars [9]. At other elevations, conditions vary between 758-658 K and 110-47 bars. Venus' atmosphere consists of  $\text{CO}_2$  with traces of noble and chemically active gases including  $\text{SO}_2$  [10]. Weathering of rocks on Venus is therefore likely dominated by oxidation reactions [11]. Studying alteration processes of rock compositions at varying conditions may therefore contribute to understand which processes/materials can cause the differences in dielectric properties between plains and mountain tops [8]. While the majority of previous models focus on reactions of specific minerals with atmospheric gases [11], here we use whole-rock compositions and model stable mineral phases at Venus conditions: temperature, pressure, oxygen and sulfur fugacities.

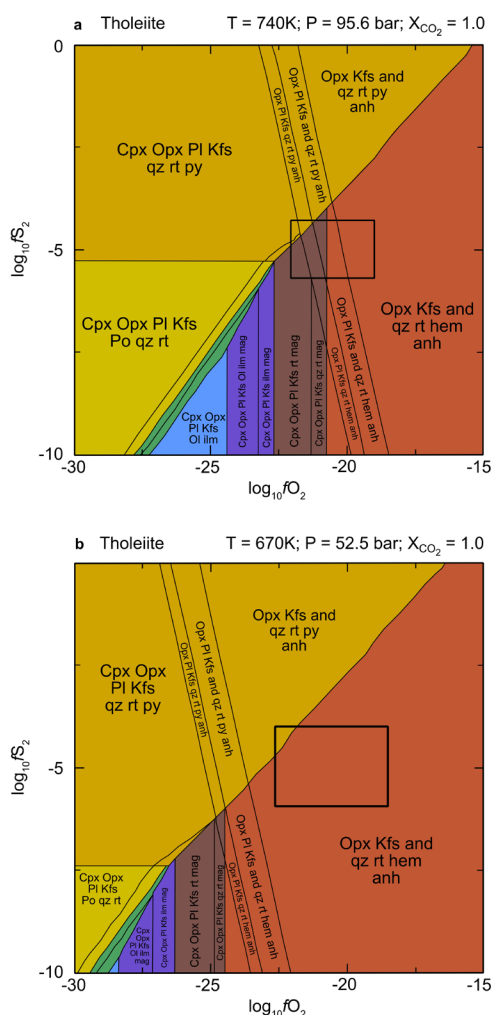


Figure 1: Phase relations as a function of oxygen and sulfur fugacities for a Venus basalt at conditions of (a) the modal planetary radius, and (b) mountain tops. Black boxes represent Venus conditions. Colors represent these phase fields/assemblages: red – hematite (hem); gold – pyrite (py); yellow – pyrrhotite (Po); brown – magnetite (mag); purple – magnetite + ilmenite; blue – ilmenite (ilm); green – ilmenite + pyrrhotite.

## 2. Methods

### 2.1 Model parameters

Phase diagrams are calculated with the Gibbs free energy minimization software *Perple\_X* 6.8.6 [12] using the internally consistent thermodynamic data set of Holland and Powell [13]. The oxides MnO, P<sub>2</sub>O<sub>5</sub>, and Cr<sub>2</sub>O<sub>3</sub> are not considered in our calculations due to their relatively low abundances and/or an incomplete set of solid solution models. We use the following solid solution models: olivine (Ol) and pyrrhotite (Po) [14]; clinopyroxene (Cpx) [15]; orthopyroxene (Opx) [16], plagioclase (Pl) [17], and K-feldspar (Ksp) [18]. Rutile (rt), ilmenite (ilm), magnetite (mag), hematite (hem), pyrite (py), anhydrite (anh), and andalusite (and) are treated as pure phases. The gas is modeled as a fluid and its properties are calculated by a Compensated-Redlich-Kwong equation of state [14]. Oxygen and sulfur fugacities are treated as independent variables.

### 2.2 Input parameters

We use a tholeiitic basalt composition based on Venera 14 rock analyses [3] and terrestrial analogs [19] for elements not analysed by the lander (in wt%: 48.7 SiO<sub>2</sub>, 1.3 TiO<sub>2</sub>, 17.9 Al<sub>2</sub>O<sub>3</sub>, 8.8 FeO, 8.1 MgO, 10.3 CaO, 2.4 Na<sub>2</sub>O, 0.2 K<sub>2</sub>O [20]). Phase equilibria are calculated at surface conditions of Venus at the level of modal planetary radius: 740 K and 95.6 bar [9]; and at conditions relevant for higher elevations: 670 K and 52.5 bar. The fluid/gas is defined as pure CO<sub>2</sub>. Oxygen and sulfur fugacities are chosen to cover a large range of conditions but include the estimated values on Venus surface with  $f_{\text{O}_2}$ : 10<sup>-20</sup> - 10<sup>-21.7</sup>, and  $f_{\text{S}_2}$ : 10<sup>-4</sup> - 10<sup>-6</sup>.

## 3. Results

Figure 1 shows the calculated phase stabilities for the tholeiitic compositions at  $P$ - $T$  conditions resembling surface conditions on Venus at modal planetary radius (Fig. 1a) and elevated areas (Fig. 1b). The black boxes represent estimated oxygen and sulfur fugacities for Venus including larger uncertainties for higher elevations. At conditions of the modal planetary radius, oxygen and sulfur fugacities result in the stability of both magnetite as well as hematite + anhydrite in addition to silicates and rutile. At lower  $P$ - $T$  conditions, magnetite is stable at much lower oxygen fugacities and would therefore not be

part of a stable assemblage, assuming that oxygen and sulfur fugacities are not significantly different.

## 4. Discussion and Conclusions

Uncertainties mainly derive from the thermodynamic data available for minerals used in our calculations and the lack of precise data of Venus' surface conditions, especially at higher elevations. The precise prediction of mineral phases is therefore rather difficult. However, even within a larger range of oxygen and sulfur fugacities (Fig. 1b), we can conclude that the assemblage of hematite + anhydrite ± pyrite is the stable assemblage at lower  $T$  (and  $P$ ) conditions and may be responsible for the observed high dielectric properties of some mountain tops negating the need for uncommon phases, whereas the conditions at the modal planetary radius are more favorable for magnetite.

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