

VAPOR TRANSPORT, WEATHERING, AND THE HIGHLANDS OF VENUS; Robert A. Brackett, Bruce Fegley Jr., and Raymond E. Arvidson, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis MO 63130

Introduction A one-dimensional finite-difference vapor transport model shows the diffusive migration of 0.01 to >10 micrometers per year of moderately to highly volatile phases (e.g., metal halides and chalcogenides) from hot lowlands (740 K) to cold highlands (660 K) on Venus. The diffusive transport of volatile phases on Venus has implications for the interpretation of Magellan radar observations, weathering models, and surface geochemistry.

The microwave emissivity of the highlands of Venus (0.3–0.6) is lower than that of the lowlands (0.8–0.9) [1], and has been attributed to highland surfaces with unusual chemical compositions and/or textures including: the presence of pyrite [1], perovskite [2], ferroelectrics [3], decimeter-scale voids [4], or a low-loss soil layer [5]. Here, we investigate the effects of vapor transport of volatile phases and discuss possible mechanisms for producing the inferred highlands signatures.

At the global mean temperature, $T \sim 740$ K, vapor pressures of nearly all metal halides and chalcogenides are 10^{20} times greater than on the Earth ($T \sim 288$ K) [6]. From 0 to 10 km elevation, vapor pressures of metal halides and chalcogenides drop by 1–5 orders of magnitude. The net effect of high vapor pressures and strong concentration gradients is that the venusian highlands act as “cold traps” for volatile vapors [7; 8]. We focus on metal halides and chalcogenides because they are commonly observed in terrestrial volcanic gases and sublimates (see Table 1.) [9–12]. Chalcophilic and volatile elements in volcanic gases are enriched up to 8 orders of magnitude relative to associated basalts for ocean island basaltic volcanism and arc volcanism [10; 13; 14]. Elements with the largest enrichment factors include: Se, S, Cl, Ir, F, Sn, Br, Cd, Au, As, Zn, Cu, Pb, Hg [13; 14]. Metal halides and chalcogenides may also be products of chemical weathering of basaltic minerals.

Model Description Vapor transport is modeled using a one-dimensional box model composed of 100 isothermal 10-km long pairs of boxes (one atmosphere and one solid). The temperature range is 740 K to 660 K. Mass is transferred between atmosphere boxes through eddy diffusion, governed by Fick’s Law [15; 16]. The meridional eddy diffusivity, K_{eddy} , of the near-surface atmosphere is estimated as $10^8 \text{ cm}^2 \text{ s}^{-1}$ from observed Venera surface wind velocities, u , [17] as $K_{\text{eddy}} \sim uH$, where H is scale height and by analogy to the terrestrial troposphere [18]. Mass is transferred from surface to atmosphere through Langmuir evaporation. Transfer from the surface to the atmosphere occurs when the partial pressure in a gas reservoir is less than the equilibrium vapor pressure. Evaporation occurs only if solid material is present. Mass is transferred from atmosphere to surface through condensation. If the partial pressure in a gas reservoir exceeds the equilibrium vapor pressure, mass is condensed until the equilibrium vapor pressure is reached. Mass transfer is solved as a function of time using a finite-difference method. The total mass is conserved. Initially, the mass in each gas reservoir is determined from the equilibrium vapor pressure for that reservoir. Each solid box begins with a uniform thickness (i.e., uniform mass).

Model Results Figure 1 shows results for model runs using high, moderate, and low volatility, $K_{\text{eddy}} = 10^8 \text{ cm}^2 \text{ s}^{-1}$, and a uniform initial surface layer thickness of 1 cm spread over the entire grid. The thickness of the surface layer is plotted as a function of time versus elevation above mean Venus radius. Transport of several cm of material to high elevation occurs over time scales of thousands to millions of years (for high and moderate volatility phases). Little transport occurs for low volatility phases. Three general features are observed. First, the hottest reservoir with solid material loses material to colder boxes and gains no material. Also, the average residence time is inversely proportional to T . Therefore, the transition from areas with no surface material to areas with enhanced (greater than initial) surface layer thicknesses is abrupt. Second, material accumulates at the coldest reservoir (highest elevation) because of mass balance and down-gradient vapor transport. Third, transport of material to the highlands occurs nonlinearly due to the exponential dependence of vapor pressure on T . The rate of transport is, to first order, linearly proportional to K_{eddy} . Figure 2 shows the volatility of selected metal halides and chalcogenides compared to the high, medium, and low volatility runs. Table 1 lists metal phases found near terrestrial volcanic vents and fumaroles.

Discussion Sufficiently thick condensate layers would be detectable in Magellan emissivity data. For a two-layer infinite half-space, the microwave emissivity, e , from the surface is

$$e = 1 - [R_1 + R_2(1 - 2R_1)L^2](1 - R_1R_2/L^2)^{-1}$$

where R_1 and R_2 are the directional power reflectivities (from Fresnel’s laws) of the 1st and 2nd layer, respectively and L is the loss factor in the 1st layer [19], assuming layer thicknesses \geq wavelength of the radar, Rayleigh-Jeans approximation, phase incoherency and no volume scattering in the coating layer. For selected metal halides and chalcogenides, thin (\leq few cm) layers have sufficiently high dielectric constants to match the observed highland emissivities. The microwave dielectric constants of WO_3 , SbSI, PbTe, PbSe, PbO, PbS, Sb_2S_3 , Sb_2Se_3 , PbCl_2 , and TiCl (halides and chalcogenides whose metals are enriched in volcanic emissions [13; 14]) are 6,000–90,000, 2,000–50,000, 400, 280, 200, 190, 180, and 110 respectively [20]. WO_3 and SbSI are ferroelectric [3].

Volatile phases may speed mechanical and chemical weathering. At equilibrium with a saturated fluid, large crystals grow at the expense of small crystals, minimizing Gibbs free energy [21]. Large crystals will exert sufficient pressure to mechanically fracture rock along pores and cracks, analogous to salt weathering on the Earth [21].

Other lines of evidence also suggest the importance of vapor transport on Venus. It is possible that volatiles (perhaps metal halides or chalcogenides) may be detectable as low-altitude hazes on Venus. [22] found increases in the scattering cross-section between altitudes of 5.8 – 6.4 km that are compatible with presence of low-altitude hazes. The failure of several instruments aboard Pioneer Venus Entry Probes at 12.5 km elevation may be due to conductive metal phases shorting out external instruments [8]. A metal halide or chalcogenide is a likely candidate. A highland

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lander capable of elemental analysis (*e.g.*, XRF or α -particle backscatter) would provide direct evidence of the role of vapor transport.

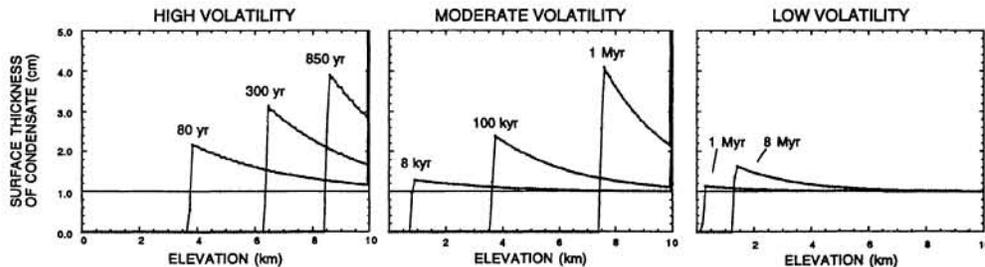


Figure 1. Thickness of surface layer vs. elevation as a function of time. High volatility corresponds to a $P_{vap}(740\text{ K}) = 10^{-3.5}$, $P_{vap}(660\text{ K}) = 10^{-5.2}$. Moderate volatility corresponds to a $P_{vap}(740\text{ K}) = 10^{-6.7}$, $P_{vap}(660\text{ K}) = 10^{-8.7}$. Low volatility corresponds to a $P_{vap}(740\text{ K}) = 10^{-9.6}$, $P_{vap}(660\text{ K}) = 10^{-12.2}$.

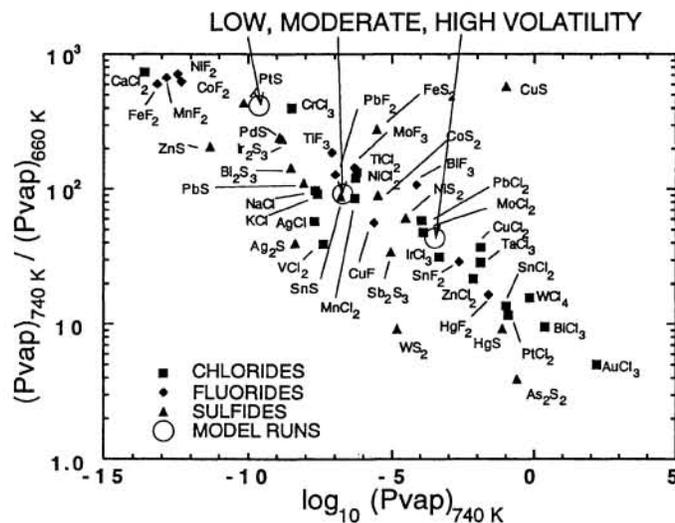


Fig. 2. Ratio of $P_{vap}(740\text{ K})$ to $P_{vap}(660\text{ K})$. Small closed symbols correspond to selected metal halides and sulfides [6]. Large open circles correspond to model runs.

TABLE 1. Metal Phases Observed as Terrestrial Volcanic Sublimates^a

Mineral Name	Chemical Formula
Anglesite	PbSO ₄
Cassiterite	SnO ₂
Chalcocyanite	CuSO ₄
Chloromagnesite	MgCl ₂
Contunnite	PbCl ₂
Covellite	CuS
Cs-K Sulfate	not identified
native elements	As, Pb, S, Se, Te, Tl
Fluorite	CaF ₂
Galena	PbS
Galenobismutite	PbBiS ₄
Halite	NaCl
Hieratite	K ₂ SiF ₆
Hydrophilite	CaCl ₂
Lawrencite	FeCl ₂
Magnetite	Fe ₃ O ₄
Massicot	PbO
Mn-bearing wolframite	(Fe,Mn)WO ₄
Nanotite	CuCl ₂
Orpiment	As ₂ S ₃
Re-molybdenite	(Re,Mo)S ₂
Realgar	AsS
Scacchite	MnCl ₂
Scherbinitite	V ₂ O ₅
Se-bearing minerals	not identified
Sphalerite	ZnS
Sylvite	KCl
Tl-bearing minerals	not identified

a. Data taken from [9-12]

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