

Vapor Pressure, Vapor Composition and Fractional Vaporization of High Temperature Lavas on Io. B. Fegley, Jr.¹, L. Schaefer¹, and J. S. Kargel², ¹Planetary Chemistry Laboratory, Department of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130-4899, ²U.S. Geological Survey, Flagstaff, AZ 86001. E-mail: bfegley@levee.wustl.edu, laura_s@levee.wustl.edu and jkargel@usgs.gov

Introduction: Observations show that Io's atmosphere is dominated by SO₂ and other sulfur and sulfur oxide species, with minor amounts of Na, K, and Cl gases. Theoretical modeling [1-3] and recent observations [4] show that NaCl, which is produced volcanically, is a constituent of the atmosphere. Recent Galileo, HST and ground-based observations show that some volcanic hot spots on Io have extremely high temperatures, in the range 1400-1900 K [5-7]. At similar temperatures in laboratory experiments, molten silicates and oxides have significant vapor pressures of Na, K, SiO, Fe, Mg, and other gases. Thus vaporization of these species from high temperature lavas on Io seems likely. We therefore modeled the vaporization of silicate and oxide lavas suggested for Io. Our results for vapor chemistry are reported here. The effects of fractional vaporization on lava chemistry are given in a companion abstract by Kargel et al. [8]

Method: We use the MAGMA code developed by Fegley and Cameron [9]. The MAGMA code simultaneously solves for the activity coefficients of the oxides in a non-ideal melt, vapor-melt equilibrium, and vapor phase equilibrium. Thirty gases and 36 melt species of the elements Si, Mg, Fe, Al, Ca, Ti, Na, and K are included in our modeling. A list of these species and thermodynamic data is given by Fegley and Cameron [9].

We considered: (1) vaporization of erupted lavas without any fractional vaporization and (2) continuous fractional vaporization of lavas. Fractional vaporization is modeled by incrementally removing vapor (after complete equilibration), recomputing the bulk elemental composition of the magma and vapor, and reequilibrating the system. The actual behavior of lavas on Io is plausibly somewhere between these two extremes as lavas erupted at 1400 K and higher probably lose some volatiles.

We made computations for a wide variety of lava compositions over 1700-3000 K. The MAGMA code assumes a completely molten system, so we restricted our calculations to temperatures above the liquidus temperatures of the lavas modeled. The 95 compositions studied included: rhyolite, basalt (tholeiitic and alkali), komatiite, dunitite, other ultramafic compositions, and calcium-aluminum rich inclusions (CAIs). The literature analyses were recomputed on a volatile-free basis. Elements other than those listed above were also excluded. Here we focus on basalts and komatiites. We describe results for CAI-type magmas in [8].

Results: We first discuss the total vapor pressure over the evaporating lavas. We then discuss the initial vapor composition. Finally, we describe the fractional vaporization of the systems.

Equilibrium Vapor Pressure: The initial vapor pressures of the lavas are temperature-dependent and increase with increasing temperature. At 1900 K, the vapor pressure of a continental tholeiitic basalt [10] composition is 10^{-2.7} bars and the vapor pressure of a Barberton-type komatiite [11] is 10^{-2.8} bars. These pressures are orders of magnitude larger than the ambient atmospheric pressure of Io (10⁻⁸ bars [12]).

We found that the total vapor pressure is not diagnostic of lava composition. For instance, at 1900 K, the range of vapor pressures for tholeiites is 10^{-2.8} to 10^{-2.7} bars whereas the range for komatiites is 10^{-3.3} to 10^{-2.6} bars.

Initial Vapor Composition: Figure 1 shows the initial vapor composition over tholeiitic basalt and Barberton komatiite lavas. The initial vapor composition for all lavas studied is dominated by Na, K, O₂, and O. These gases are more abundant than all other species by several orders of magnitude. Over the temperature range plotted, the abundances of Na, K, and O₂ are essentially temperature-independent, whereas the abundance of every other species is temperature-dependent.

At the low end of our temperature range (1700-1900 K), the fifth most abundant gas is the e(gas) produced by thermal ionization of Na (g) and K (g) to Na⁺ (g) and K⁺ (g). At these lower temperatures, K⁺ (g) is always more abundant than Na⁺ (g). However, there is a temperature-dependent relationship for the extent of thermal ionization: $(K^+/K)/(Na^+/Na) = K_2/K_1$, where K₁ and K₂ are the temperature-dependent equilibrium constants for the ionization reactions for Na (g) and K (g), respectively. Observations of these four species could therefore help constrain the temperature of the volcanic gas.

As temperature increases, however, the abundances of other metal gases exceeds that of the thermal ionization products. Particularly important are FeO (g), Fe (g), and SiO (g), which are the first three gases to become more abundant than the electron gas. For ultramafic lavas such as komatiites, Mg (g) is also abundant as temperature increases. Note that the two graphs in Fig. 1 are nearly identical, except for the magnesium gases, which are significantly more abundant above the komatiite than above the tholeiite. Detection of Mg (g) during an eruption on Io would indicate an ultramafic composition.

As of yet, there has been no detection of any of the metals Fe, Si, Mg in the Io plasma torus. Na et al. [13] set an upper limit for the abundances of these metals relative to sodium based upon the non-detection of the neutral atoms. The abundances of the metal gases which we are predicting are, however, well below the upper limit set in [13] by several orders of magnitude for either lava in Fig. 1.

Fractional Vaporization: Figure 2 shows the evolution of the vapor composition over a lava which is losing mass due to vaporization at 1900 K. The alkalis which dominate the initial vapor are lost from the system after a small amount of fractional vaporization: by ~7% vaporized for the tholeiite and ~4% vaporized for the komatiite. The pressure drops several orders of magnitude after the loss of alkalis and becomes dominated by silicon, iron and magnesium gases as well as O₂ and O.

Iron is the next element to be lost from the system, after the alkalis. This produces Mg-rich residual compositions. Above the depleted lavas, as shown in Fig. 2, Fe(g) is more abundant than FeO(g), though the reverse is true in the initial

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vapor (see Fig. 1 at 1900 K). For basaltic compositions, SiO(g) is the most abundant gas throughout most of the vaporization, followed by O₂ and O. For ultramafic lavas, Mg(g) is also very abundant and becomes more abundant than SiO(g) as the Si abundance in the melt decreases. For some ultramafic compositions, such as dunite and meimechites, Mg(g) is always more abundant than SiO(g).

Summary: We predict that basaltic and komatiitic lavas erupted at temperatures ≥ 1700 K have total vapor pressures significantly greater than the ambient atmospheric pressure of $\sim 10^{-8}$ bars on Io. The vapor over the lavas is initially dominated by Na, K, O₂, and O gases. At temperatures of hot spots such as Pele and Pillan [5,6] the next most abundant species is the e⁻(gas) from thermal ionization of Na and K. Other important gases are FeO, Fe, SiO, and for ultramafic compositions, Mg gas. Fractional vaporization depletes the vapor and lava in alkalis and decreases the total vapor pressure by several orders of magnitude to about 10⁻⁶ bars. Then major vapor species are SiO, O₂, Fe, O, FeO, and Mg, with the latter more abundant over ultramafic lavas. Continued fractional vaporization depletes Fe and Si, leading to more refractory compositions discussed in [8]. We

recommend searching for these species above high temperature volcanic hot spots such as Pele and Pillan during eruptions: Na, Na⁺, K, K⁺, SiO, O₂, O, Mg, Fe, FeO. We call out SiO (g) in particular and suggest searches at millimeter, IR, and UV wavelengths for this important gas.

Acknowledgements: This work was supported by NASA Grant NAG5-11958.

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Figure 1: Initial vapor composition over: (a) a tholeiitic basalt, and (b) a Barberton-type komatiite.

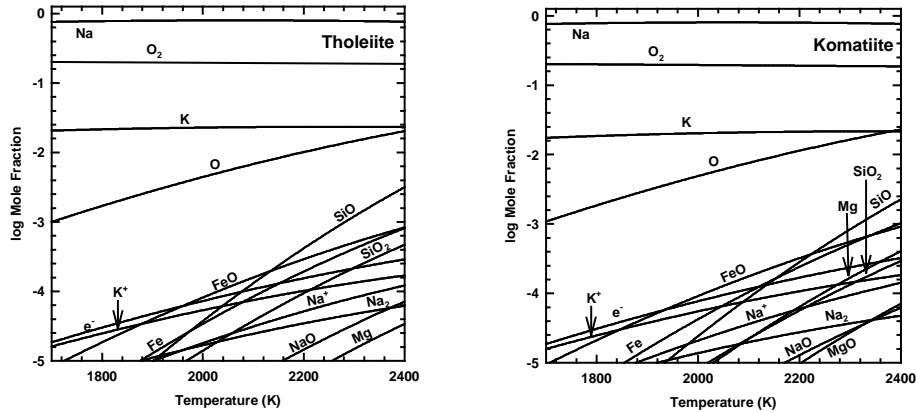


Figure 2: Vapor composition due to fractional vaporization of : (a) a tholeiitic basalt and (b) a Barberton-type komatiite. The alkalis, Na and K, are lost from the systems by (a) ~7% vaporized and (b) ~4% vaporized.

