Potassium Budget and Fractional Degree of Mantle Melting on Venus from Venera and Vega γ-ray Measurements;
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Introduction The abundance of potassium in the terrestrial planets is important for understanding interior heat production and thermal evolution [1] as well as planetary outgassing and magmatism [2]. Recent analyses of the impact crater population on Venus from Magellan radar images led to the hypothesis that the planet experienced nearly global volcanic resurfacing approximately 500 My ago [3, 4] and that volcanic activity after this event continued at a lesser, but appreciable, rate [5, 6]. The distinctive magmatic histories of Earth and Venus, despite their similarities in mass, solar distance, and presumably bulk composition [7], have been variously postulated to be the result of different styles of mantle convection on the two planets [8, 9] under the assumption that the heat production per mass, and in particular the K concentration, in Venus and Earth are approximately equal.

This assumption of equal K concentrations in both planets, although supported by the similarity of measured K/U and K/Th ratios in the generally basaltic materials sampled at Venera and Vega landing sites to those of terrestrial igneous rocks [10] and by theoretical analyses of the gravitational mixing of planetesimals during planetary accretion [11], merits re-examination. The K/U and K/Th ratios are sensitive to large uncertainties in the γ-ray measurements [12]. Further, K concentrations in the bulk silicate portions of Venus and Earth may differ because K is a moderately volatile element [e.g., 13].

Fractional Degree of Melting We assume that radioactive elements are partitioned between liquid and solid during partial melting of mantle material according to the relation

$$C_L = \frac{C_0}{K_{mode} + f_{melt}(1 - K_{stoi})} \tag{1}$$

where C_L is the mass concentration in the melt, C_0 is the mass concentration in mantle material prior to partial melting, and K_{mode} and K_{stoi} are averages of mineral partition coefficients between solid and melt weighted by the modal abundances of mantle material prior to partial melting, and by the stoichiometric coefficients of the melting reaction [14], respectively. For C_0, we assume that the U and Th concentrations in the Venus mantle lie between 18 and 29 ppb and between 64 and 94 ppb, respectively, on the basis of estimates for the bulk silicate Earth [e.g., 15] and for the bulk silicate portion of Venus [7]. The C_L values for U and Th are taken from γ-ray measurements by Venera and Vega landers [12]. Bulk partition coefficients for U and Th are assumed to be 1.2 x 10^{-3} and 2.9 x 10^{-4}, respectively [16], for both K_{mode} and K_{stoi}.

Calculated ranges of f_{melt} are shown in Figure 1a. Uncertainties, shown by horizontal lines, reflect uncertainties both in the γ-ray measurements [12] and in the mantle concentrations of U and Th [e.g., 7, 15]. The estimated f_{melt} is different for each sample. We assume, however, that both U and Th in each sample are partitioned by the same process of partial melting. Therefore a plausible range for f_{melt} during the magma genesis leading to the formation of each sample is the overlap between the calculated ranges of f_{melt} for U and Th. We do not take the measurements by Venera 8 into further consideration because the observed high concentration of radioactive elements in the sample is indicative of assimilation of crustal materials into the mantle-derived magma [17]. The smallest value of f_{melt} is then 0.021, obtained from Vega 2, and the largest value, obtained from Vega 1, is 0.16 (Figure 1a).

K Concentration in the Bulk Silicate Portion of Venus We make use of the calculated value of f_{melt} for each sample to estimate the K concentration in the bulk silicate fraction of Venus, $(K)_{bulk}$. Again we utilize equation (1), and we substitute γ-ray measurements of the surface K concentration, including experimental errors, for C_L. Partition coefficients of K between major minerals and silicate melts are taken from the literature [e.g., 14, 18]. For $K^K{}_{mode}$ and $K^K{}_{stoi}$ in equation (1), we take into account a range in possible mantle compositions, particularly in the

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modal abundance of plagioclase in the Venus mantle, because the partition coefficient of K for plagioclase is orders of magnitude higher than the other partition coefficients [14, 18].

The range in calculated $(K)_{bulk}$ for each sample is shown as a function of f_{melt} in Figure 1b. A wide range of $(K)_{bulk}$ values is allowed for each sample. However, a plausible inference is that the average K concentration in the bulk silicate portion of Venus must lie within each calculated range shown in Figure 1b (except that for the Venera 8 sample). It is clear from the figure that the estimated ranges of bulk silicate K concentration from the Vega 1 and 2 and Venera 10 samples overlap the range for the Venera 9 sample. Therefore we assume that the K budget in the bulk silicate Venus is constrained by the Venera 9 sample and is between 95 and 250 ppm (Figure 1b).

Fractional crystallization of olivine and pyroxene during gradual cooling of mantle-derived magma prior to eruption has a minor effect on our estimate of $(K)_{bulk}$, because K is as incompatible as U and Th in olivine and pyroxene. The K/U and K/Th ratios therefore do not change significantly by the crystallization of these minerals. On the other hand, K is relatively compatible in plagioclase compared with olivine and pyroxene; correcting for the possible fractional crystallization of feldspar results in an increase in the upper bound on $(K)_{bulk}$ from 250 to 300 ppm.

Discussion The calculated values of f_{melt} for Venus, at 0.02-0.16, are generally less than average values (0.15-0.2) typical of terrestrial MORBs [e.g., 19]. Lower values for Venus could be the result of somewhat lower mantle temperatures or of a lesser vertical extent of the melt-generating zone, perhaps because of a generally thicker lithosphere, beneath plains regions on Venus than beneath mid-ocean ridges on Earth. The bulk K concentration on Venus, well constrained to be between 100 and 300 ppm regardless of fractional crystallization, shows good agreement with the K abundance in the bulk silicate Earth [e.g., 2, 7, 15]. Earth and Venus thus have similar internal heat production.

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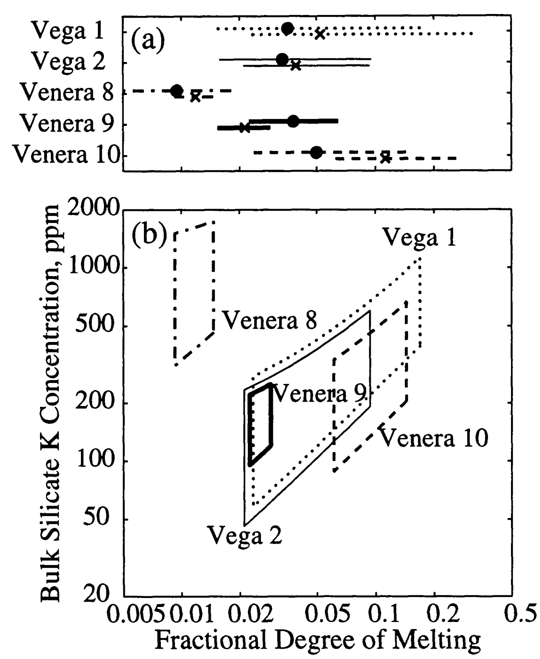

Figure 1. (a) Nominal estimates of fractional degree of mantle melting calculated from γ-ray measurements of U (filled circles) and Th (crosses) in Venus surface materials (Table 1) and assumed mantle concentrations of the radioactive elements. (b) Estimates of the K concentration in the bulk silicate fraction of Venus for each sample in (a) from γ-ray measurements of the K concentration in surface material. Line type: Vega 1 (dotted lines), Vega 2 (thin solid lines), Venera 8 (dot-dash lines), Venera 9 (thick solid lines), and Venera 10 (dashed lines).