

## MELTING VENUS: POTENTIAL GEOCHEMICAL DIAGNOSTICS OF MANTLE SOURCE DEPTH

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### Introduction

Volcanism on Venus has produced a rich array of volcanic landforms [1], which in turn suggests a broad range of magma production and differentiation environments. In the next decade, it is possible that one or more landers associated with New Frontiers or Flagship class missions to Venus will provide new geochemical observations of the Venus surface. The goal of this work is to make an initial assessment of how such geochemical observations may help to constrain magma production depths on Venus.

### Magmatic Environments on Venus

Volcanism on Venus occurs in a variety of geologic environments that suggest varying mantle source depths for magma production. Volcanic rises such as Beta Regio and Atla Regio are likely formed over hot, upwelling mantle plumes [2, 3], with magma produced as deep as 170 km (5 GPa) [4]. Coronae are probably formed by diapiric upwellings [5], possibly under regions of lithosphere that are thinner than for volcanic rises [6] and thus melting occurs at lower pressures. Large flow fields are commonly associated with rifts and fracture belts [7], for which the observed fracturing and extension suggests a relatively thin lithosphere and low pressure magma generation.

In preparation for proposed future spacecraft missions to Venus, we therefore consider the extent to which likely geochemical instrumentation on short-lived landers may be able to place constraints on mantle source depth. We do not consider the possible effects of near-surface fractionation, which are discussed in another abstract [8]. Such fractionation likely has occurred in some places. For example, shield fields on Venus may contain 100 or more small shields in a single large volcanic field [9, 10]. Such fields are likely fed by a single large magma chamber, which would provide an environment suitable for shallow magmatic fractionation. The proposed environment is similar to the Marius Hills on the Moon, for which gravity observations provide clear evidence for a regionally extensive magma chamber [11].

### The Mantle Source Composition

An essential aspect of any magma production calculation is the assumed composition of the mantle source region. We focus specifically on basaltic vol-

canism, which appears to dominate the surface of Venus. Issues related to production of non-basaltic magmas on Venus are considered in [12]. Numerical accretion simulations suggest that there was probably considerable radial mixing within the solar nebula [13]. Thus, to first order, it is reasonable to assume that the mantles of Venus and Earth had similar primordial compositions. For this reason, we will assume for the purpose of this work that the Venus mantle is similar to the terrestrial KLB-1 mantle peridotite [14], which is representative of basaltic source region compositions on Earth [15]. The available geochemical measurements from the surface of Venus are basically consistent with this, but with large measurement uncertainties [16, 17]. We assume a dry mantle source region, which is consistent with the apparent absence of a low viscosity asthenosphere in the mantle [2].

We note, however, that the preservation of distinct oxygen isotopic reservoirs in many parts of the solar nebula [18] implies that radial mixing in the nebula was at best imperfect. As a result, there may well be subtle but important differences in mantle composition between Venus and Earth. Results for Mars derived from the chemistry of the martian meteorites may be instructive. In comparison to Earth, Mars appears to have a somewhat lower Mg number (the molar Mg/(Mg+Fe) ratio) and to be enriched in alkalis [19, 20]. Together, the two effects lower the martian mantle solidus by about 35 K relative to terrestrial peridotites [21], which has a significant effect on the calculated magma production [22]. Based on these considerations, we may also consider other peridotite starting compositions to assess the sensitivity of our results to small changes in mantle source region composition.

### Geochemical Measurements

For the purpose of this work, we assume that a relatively basic suite of geochemical measurements will be possible on the next generation of Venus lander. These include measurements of major element composition by an X-Ray Fluorescence Spectrometer, of U, Th, and K by a Gamma-Ray Spectrometer, and of mineralogy by an X-Ray Diffraction Spectrometer. X-Ray Fluorescence and Gamma-Ray spectroscopy have both been performed at a variety of locations on Venus [23, 24]. Because U and Th are both refractory (and thus likely to have been initially present in chon-

ditric abundances) and highly incompatible (and thus concentrated in the melt phase), the Gamma-Ray Spectrometer might be thought of as a “partial melt fraction meter”, although interpretation of such measurements obviously depends on whether a given mantle parcel has passed through the melting zone on more than one occasion. Possible approaches for measuring important minor and trace elements such as Na, Ni, and Co are described in [17]. X-Ray diffraction might be done with an approach similar to the ChemMin instrument suite being developed for Mars Science Laboratory [25]. If it can be adapted for use at Venus ambient conditions (including the need for extended integration periods), it may provide at least semi-quantitative constraints on the rock mineralogy. Finally, some sort of drill system is needed to core beneath any surface weathering layer.

### Magma Composition Modeling

The observations cited above suggest that magma on Venus may form at a broad range of pressures, from about 0.2 GPa at the base of the crust to perhaps 5 GPa in mantle plumes. The available petrology literature [e.g., 26, 27] suggests that simply varying magma production depth for a fixed mantle source composition can imprint recognizable chemical fingerprints on the resulting basalts.

To further explore this, we are performing a series of melting calculations using the thermodynamically based MELTS and pMELTS programs [28, 29]. For our specified mantle source composition, we consider temperatures that result in melt fractions ranging from a few percent to as much as 20%. The upper end of the melt fraction range on Venus is not known, but presumably the highest melt fractions occur in shallow melting environments such as rift systems. For each combination of temperature and pressure, we calculate the liquid composition that is in equilibrium with the mantle source composition. Melting calculations up to 1 GPa are done with MELTS and calculations at 1-3 GPa are done with pMELTS. Although melting may occur at pressures greater than 3 GPa on Venus [4], we do not model this because of the limitations in the experimental thermodynamic database used in pMELTS [29].

Each magma composition is then transported to the surface without fractionating at intervening depths. It is crystallized at the ambient surface pressure and the normative mineralogy is calculated. We are assessing possible trends in basalt elemental composition and mineralogy as a function of melting depth and melt fraction. For example, does the source depth cause

changes in the Mg number or the alkali abundance? How do the relative abundances of plagioclase, clinopyroxene, orthopyroxene, and olivine vary with initial melting depth? Can the appearance or disappearance of accessory minerals be used as a melting depth indicator? Because of uncertainties in the mantle source composition and because we have not included near-surface fractionation, our results may not provide precise melting depth indicators. Moreover, in practice melting will typically occur over a range of depths, which will at least partially blur the patterns in real rocks. Our hope, however, is to identify trends which are sufficiently robust that they can at least serve as guides to the initial melting depth.

### References

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