Implications of Recent Hotspot Volcanism on Venus for the Interior, Surface, and Atmosphere. S. E. Smrekar[1] and C. Sotin[1], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA; ssmrekar@jpl.nasa.gov, christophe.sotin@jpl.nasa.gov.

Introduction: Magellan radar and topography data revealed the presence of nine large broad topographic swells with large volcanoes near their crests. These features are believed to be geologic analogs to terrestrial hotspot swells such as Hawaii. Modeling of the gravity signature of these features implied the presence of an active mantle plume at depth [e.g. 1]. Recent data from the Venus Express mission showed variations in the 1 micron signature at the 3 hotspots imaged. The interpretation of derived high emissivity anomalies in the VIRTIS data set as indicating recent volcanism corroborates the presence of an active plume [2].

This study examines the mantle conditions necessary to produce a limited number of plumes at the core mantle boundary using 3D numerical models of convection. Producing a limited number of robust plumes capable of generating pressure release volcanism beneath a conductive lid 100-300 km thick [1] requires a relatively low mantle viscosity, on the order of 10^{20} Pa s. Further, the balance between internal heating and bottom heating implies that the mantle of Venus may be heating up. Below we describe our numerical experiments and the broader implications of present day hotspot volcanism for resurfacing and volatiles in the interior and atmosphere.

Method: We employ the OEDIPUS code [3,4] to simulate thermal convection in Venus mantle. This code uses the cubic-sphere geometry to solve the equations describing the conservation of mass, momentum and energy in a 3D spherical geometry. These equations include the Boussinesq approximation and an infinite value of the Prandtl number. The fluid is characterized by several parameters including thermal diffusivity (K), thermal conductivity (k), thermal expansion (α), density (ρ), and viscosity (η), which is strongly temperature dependent (but not depth dependent). The use of the cubic sphere allows us to solve the equations in one sixth of the total sphere with periodic boundary conditions on the vertical planes. The temperature is imposed at the surface (T_0) and at the core mantle boundary (T_1). Free-slip or no-slip conditions can be applied on the horizontal planes. For all cases we assume a surface temperature of 735°K, K = 1 x 10^{-6} m^2/s, α = 3 x 10^{-5} K^{-1}, k =1 W K^{-1} m^{-1}, ρ = 3500 kg/m^3, gravity = 8.87 m/s^2, a core radius of 3120 km, and a planetary radius of 6052 km. Most cases have a grid spacing of 123^3; 4 cases have 256 elements vertically. The temperature dependence of the viscosity is equivalent to an activation energy of 450 kJ/mole.

Results: We ran 17 cases with a wide range of non-dimensional internal heating rate, Hs (0-15), and temperature differences across the mantle, ΔT (840-2280K). Mantle viscosities of 10^{20} Pa s and 10^{21} Pa s were also examined. The resulting Rayleigh number range is 1.3x 10^5 to 6.1x10^7. We find that the number of plumes is proportional to the convective Rayleigh number and $(\delta d)^{-1/2}$, where δ is the thickness of the hot or cold boundary layer, and d is the depth of the mantle. For some values of ΔT and Hs, the hot thermal boundary layer is either non-existent or has too small a temperature difference across the boundary to develop plumes. The smallest number of number of hot plumes (20-30 globally), occurs with no internal heating and produces no pressure release melting. Some cases with no internal heating and ΔT values in excess of 1100K did produce melting despite conductive lid thicknesses >450 km thick.

High Rayleigh number cases with significant internal heating and low viscosities produce realistic lithospheric thicknesses and pressure release melting using a dry wet solidus (Fig. 1). In these cases, dry melting occurs through out the upper mantle. Only two cases with a mantle viscosity of 10^{20} Pa s and very large temperature differences across the mantle (1710 and 2280 K) produce melting with a dry solidus (Figure 1).

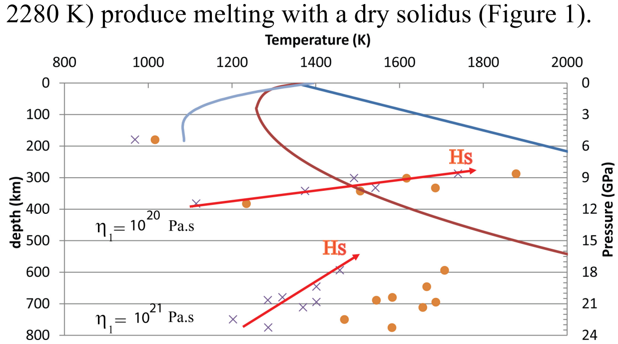

Figure 1. Horizontally averaged temperatures (crosses) at the base of the conductive lid are compared with the dry and wet melting temperatures. The right most line is the dry solidus, the middle curve is the wet solidus, and the left partial curve is the low water solidus [5]. Filled circles represent the temperatures with the adiabatic correction. Values at depths between 300 and 400 km correspond to the low viscosity cases. Arrows indicate increasing amount of internal heating. The non-Newtonian case occurs at a depth less than 200 km.

One case with a low activation energy was conducted to simulate a non-Newtonian rheology [6]. This case has a much thinner predicted conductive lid thickness. However the temperature of the equilibrium mantle temperature is too low to predict melting.

Discussion: The presence of recent volcanism at hotspots (and apparently no where else, at least at the ~100 km resolution of VIRTIS data) has important implications for the interior, as well as potentially for surface geology, and the atmosphere. Formation of mantle plumes requires a hot thermal boundary layer. The formation of a relatively small number of plumes at the core-mantle boundary further implies the mantle Rayleigh number must be relatively high thus requiring a hot, low viscosity mantle. Further the need to balance internal heating versus bottom heating implies that the mantle on Venus may be heating up.

Including even modest amounts of internal heating requires that the mantle viscosity is low (10^{20} Pa s) compared to terrestrial values in order to maintain thin conductive lids and produce melting. This is consistent with a hotter mantle due to the presence of a stagnant lid. Wet melting is predicted through out much of the upper mantle. Thus the upper mantle may be lacking in light elements and be more fully outgassed than the lower mantle. Volcanism may have gone through a transition from more wide-spread, wet melting in the upper mantle to more localized melting in mantle plumes carrying unmelted, volatile rich material from depth (Fig. 2). This could imply a transition from wide-spread plains volcanism to isolated hotspot volcanism. This is the pattern seen by VIRTIS. However, the view is limited to a resolution of 100 km, and the southern hemisphere.

The volume of the upper mantle is ~1/4 that of the whole mantle, consistent with estimates of the amount of outgassing estimated from isotopic ratios [7]. Depending on the water content of the lower mantle, deep plumes may contribute to present-day atmospheric water via volcanic outgassing. Assuming 50 ppm water in mantle, 10 plumes with a buoyancy flux of 500 kg/s continuously erupting for 4 m.y. will outgas an amount of water on the order of that in the lower atmosphere [8].

We have not yet exactly reproduced the desired number of plumes, perhaps due to time-dependent effects, lack of phase transitions, or other limitations. In future work, we will examine the time dependence of the plumes and how many would actually produce an observable signature.

The current interpretation of the high emissivity anomalies as indicating a lack of surface weathering implies that weathering may take months to years, rather than the mere days, as implied by extrapolation of laboratory experiments [9,10]. Further, the most likely weathering product is hematite, but others such as calcite or quartz can not be ruled out.

The presence of recent volcanism can not be used to distinguish between current models of resurfacing. The estimated volumes of volcanism seen at these 3 regions is consistent with all types of resurfacing models [2]. By analogy with Earth, rates of volcanism are expected to be highly variable on the timescales of days to years. Thus only extreme rates of present day volcanism would be inconsistent with a major pulse of resurfacing early in the history of Venus.

Conclusions: Using 3D calculations of the number of plumes including internal heating and the prediction of pressure release melting adds important new constraints on interior evolution. We find a relatively low viscosity mantle, with either dry melting or wet melting and very high mantle temperatures. Although the upper mantle may have melted sufficiently to outgas, the lower mantle may still contain appreciable water, and could supply current concentrations in the lower atmosphere.

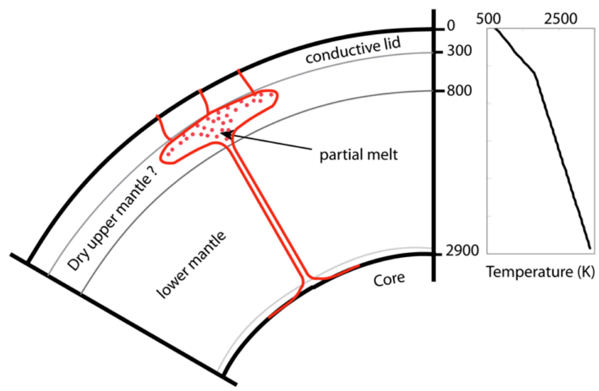

Figure 2. Schematic view of an upwelling hot plume based on results of the present study. The right panel shows the horizontally averaged temperature for one case.

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