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Mantle Plumes on Venus: Implications for Mantle Viscosity, Water Content, and Melting

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Abstract

Gravity, topography, and VIRTIS emissivity suggests the presence of ~10 deep, active mantle plumes on Venus. This study predicts the number of plumes formed at the core-mantle boundary (CMB), their characteristics, and the amount of partial melt using 3D spherical simulations with large viscosities variations and internal heating. The case with the most realistic lid thickness and internal heating (3.3 TW) has a mantle viscosity of 10^{20} Pa s, and a mantle temperature difference of 1140°K, but predicts more than 70 plumes globally. Since wet melting is predicted over much of the upper mantle, over time it may have lost significant volatiles. Assuming 100 ppm water in the mantle, 10 plumes erupting for 200 m.y. will outgas approximately the amount of water in the lower atmosphere. A higher level of internal heating may be required to achieve simulations with ~10 plumes and a thinner lid. Alternatively, if the mantle is heating up due to the stagnant lid, the effect is equivalent to having lower rates of internal heating.

1. Introduction

Plumes are one of the few manifestations of mantle convection that can be readily observed on stagnant lid planets. The interpretation of high emissivity anomalies in the VIRTIS data set as indicating recent volcanism corroborates the presence of an active plume inferred from gravity and topography [1]. Plumes also represent the interface between the interior, surface and atmosphere due the resulting volcanism and outgassing.

1.1 Methods and Results

We employ the 3D spherical OEDIPUS code [2,3] with temperature dependent rheology to constrain the balance between internal heating (Hs), temperature difference across the mantle (DT), and mantle viscosity needed to produce a small number of plumes (~10) globally. 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. When even relatively small amounts of internal heating are included, a mantle viscosity of 10^{20} Pa s is needed to increase the temperature difference across the mantle. Partial melting occurs over 100s of km in the upper mantle using a wet solidus but not for a dry solidus. 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, $K = 1 \times 10^{-6}$ m^2/s, $\alpha = 3 \times 10^{-5}$ K^{-1}, $k = 1$ $W\ K^{-1}\ m^{-1}$, $\rho = 3500$ kg/m^3, $g = 8.87$ 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; two cases have 256 elements vertically. The temperature dependence of the viscosity is equivalent to using an activation energy of 450 kJ/mole.

Results: We have examined 15 cases to date (Table 1). For some values of DT and Hs, the hot thermal boundary layer (HTBL) has too small a ΔT to develop plumes (Figure 1). To date the most realistic case in terms of number of hot plumes (7x6 = 42 globally), the thickness of the conductive lid (312 km), and Hs (10) is case 15 (Table 1). The hot plumes produce pressure release melting over several 100s km in the upper mantle, but only for a wet solidus, not a dry solidus.

2. Summary and Conclusions

These results have important implications for the mantle. First, we can't predict realistic values of the conductive lid thickness or use substantial values of Hs unless the mantle viscosity is low (10^{20} Pa s) compared to terrestrial values. This is consistent with a hotter mantle due to the presence of a stagnant lid. Second, 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 widespread, wet melting in the upper mantle to more localized melting in mantle plumes carrying unmelted, volatile rich material from depth. We have not yet reproduced the very low desired number of plumes, perhaps due to time-dependent effects, lack of phase transitions, or other limitations.

Conclusions: Using 3D calculations of the number of plumes including internal heating and the prediction of pressure release melting ads important new constraints on interior evolution. We require a relatively low viscosity mantle, with only wet melting. Although the upper mantle may have melted sufficiently to outgas, the lower mantle may still contain appreciable water.

Case #	Symb	Hs	T (K°)	Bound Cond.	Visc. Pa s	Grid Size	Ra conv	Conv. Mantle T	Lid Depth (km)	Lid temp (K)
1	●	0	840	NS	1E+21	128^3	1.27E+5	0.84	991	362
2	○	0	840	FS	1E+21	128^3	2.80E+5	0.87	851	364
3	■	0	1140	NS	1E+21	128^3	1.95E+5	0.83	873	469
4	□	0	1140	FS	1E+21	128^3	4.92E+5	0.87	750	468
5	■	0	1140	NS	1E+20	128^3	4.16E+6	0.83	383	392
6	◆	0	1466	NS	1E+21	128^3	5.22E+5	0.83	358	522
7	◊	0	1466	FS	1E+21	128^3	8.45E+5	0.85	326	518
8	■	1.25	1140	NS	1E+21	128^3	4.32E+5	0.87	776	552
9	□	1.25	1140	FS	1E+21	128^3	7.75E+5	0.90	689	551
10	■	2.5	1140	NS	1E+21	128^3	8.62E+5	0.91	712	635
11	▲	2.5	1215	NS	1E+21	128^3	9.24E+5	0.91	695	667
12	✶	2.5	1290	NS	1E+21	128^3	1.07E+6	0.91	646	667
13	■	5	1140	NS	1E+20	128^3	2.42E+6	0.96	594	723
14	■	5	1140	NS	1E+20	256x128^2	2.27E+6	0.92	329	493
15	■	10	1140	NS	1E+20	256x128^2	4.06e+6	0.96	312	544

Table 1. Run parameters. Symbols are those used in Figure 1.

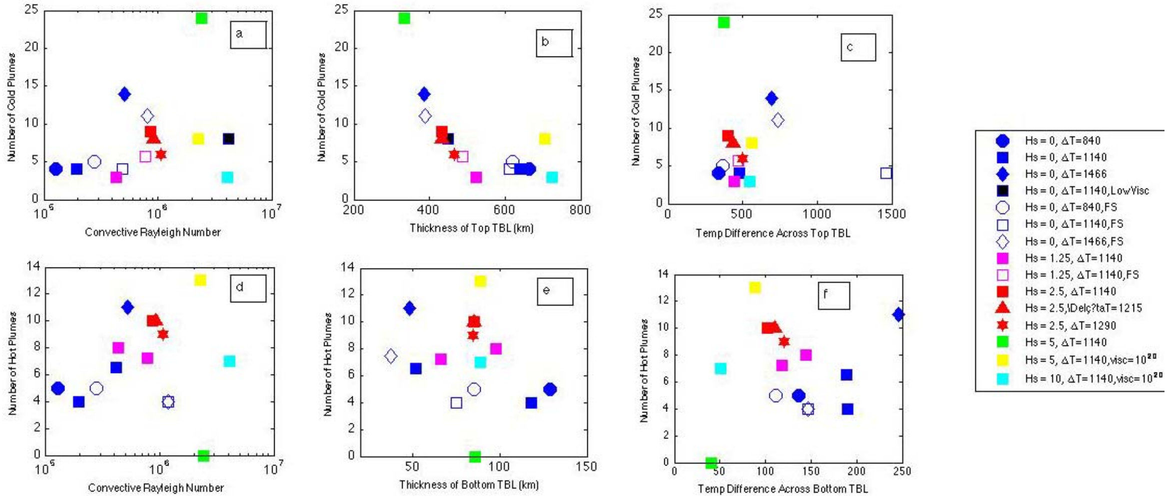

Figure 1. Number of cold plumes (top row) and hot plumes (bottom row) as a function of convective Rayleigh # and the thickness and dT across the cold & hot thermal boundary layers. Symbols correspond to those in Table 1.

3. References

[1] Smrekar S.E. et al. (2010) *Science*, *328*, 605-608.
[2] Choblet G. (2005) *J. Comp. Phys.*, 205, 269–291.
[3] Choblet, G. et al. (2007) *Geophys. Journal.* Intern., 170, 9-30.