Modeling Venusian resurfacing mechanisms: Progressive surface volcanism versus catastrophic mantle overturn, and a comparison to observed Venus topography, geoid, and thermal emissivity anomalies

Aaron C. Prunty[1] (pruntya@vt.edu), Scott D. King[1] (sdk@vt.edu)
[1]Department of Geosciences, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

INTRODUCTION

Surface observations of Venus, in particular topography, crater population distributions, and volcanic features, suggest a relatively recent global resurfacing event approximately 750 Ma [1-4].

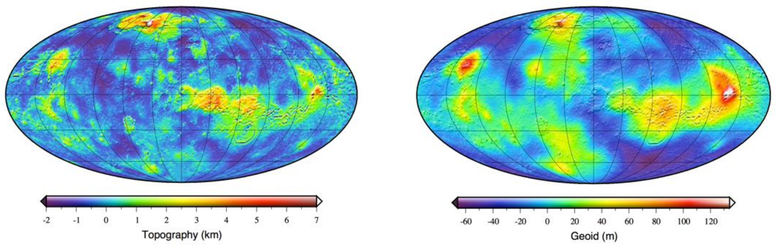

Figure 1. Venus spherical harmonic models of global topography and geoid [16].

While there are several variations and modifications, two end-member hypotheses have been proposed to explain the observed surface age of Venus: widespread, progressive surface volcanism and catastrophic overturning of the lithosphere [1, 4, 5-12].

Progressive surface volcanism, assumed to originate from deep mantle plumes [13], implies an instability at the core-mantle boundary. Convective mantle overturn, on the other hand, implies a lithospheric instability. The two end-member mechanisms therefore yield starkly different thermal evolutions of the planet [10, 14].

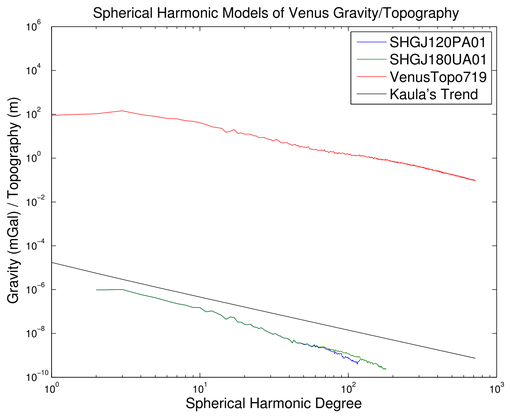

Figure 2. Spectral plot of Venus spherical harmonic gravity (SHGJ20PA01 and SHGJ180UA01) and topography (VenusTopo719) models.

Utilization of observed long-wavelength topography, global geoid, and thermal emissivity anomalies coupled with insight from numerical modeling provides a means to compare predictions from modeling the two end-member mechanisms.

MODELING

We perform high-resolution 3D spherical convection calculations using CitcomS, a finite element code that solves the principle governing equations of conservation of mass, momentum, and energy for the anelastic, incompressible, viscous, thermo-chemical convection problem:

$$\nabla \cdot u = 0$$

$$-\nabla P + \nabla \cdot \left[\eta \left(\nabla \vec{u} + \nabla^T \vec{u} \right) \right] + RaT\vec{e}_r = 0 \qquad Ra = \frac{\rho_0 g \alpha \Delta T R_0^3}{\kappa \eta_0}$$

$$\frac{\partial T}{\partial t} + \vec{u} \cdot \nabla T = \nabla^2 T + H$$

We model the catastrophic resurfacing mechanism in the stagnant lid regime following the method of van Heck and Tackley [15] using temperature-dependent rheology and lithospheric yielding to produce stagnant-lid convection with self-generating punctuated lithospheric instabilities in a spherical shell geometry:

$$\eta(T) = \eta_0 \exp\left(\frac{E}{nRT} \right)$$

$$\eta_{yield} = \frac{\sigma_{yield}}{2\dot{\varepsilon}_{II}} \qquad \eta = \left(\frac{1}{\eta(T)} + \frac{1}{\eta_{yield}} \right)^{-1}$$

Table 1. Parameters for temperature-dependent rheology and lithospheric yielding.

Quantity	Non-D Value
Activation Energy	23.03
Temperature Offset	1
Yield Stress	1e5
Reference Viscosity	1e24

We consider both degree-1 mantle overturn as well as shorter-wavelength, multiple instability cases. We run the convection calculation for at least 500 Myr model time after the overturn event and analyze the geoid, topography, and heat flow once the calculation has settled down into a quasi-steady planform.

RESULTS

We modeled the catastrophic resurfacing mechanism to infer the thermal evolution of Venus. Degree-1 and multiple, shorter-wavelength perturbations were chosen as two distinct initial conditions to test the affects of the mode of mantle overturn on the observed geoid and topography (Figure 3).

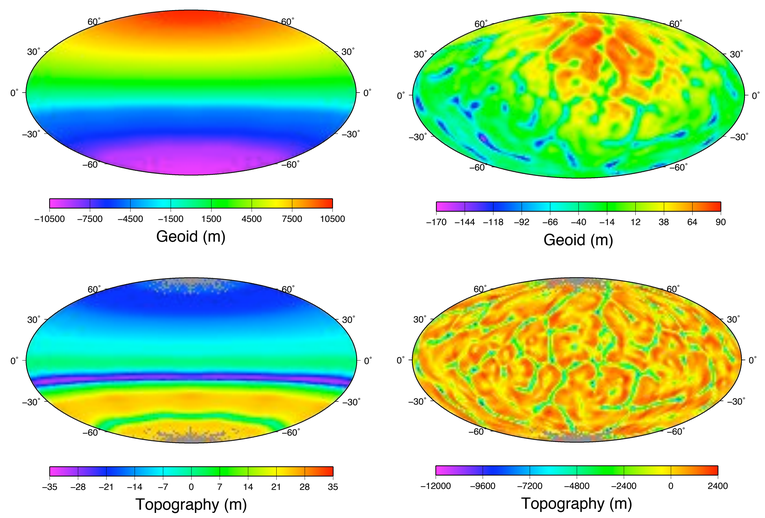

Figure 3. Comparison of geoid and topography for degree-1 mantle overturn (left) and shorter-wavelength, multiple instability subduction (right).

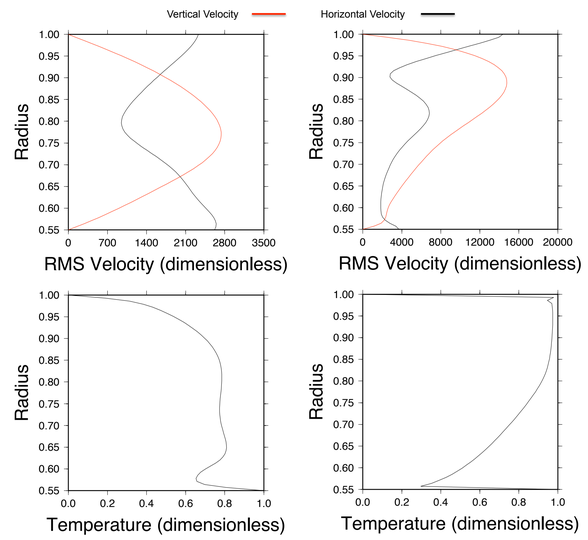

Figure 4. Comparison of rms velocity and temperature for degree-1 mantle overturn (left) and shorter-wavelength multiple instability subduction (right).

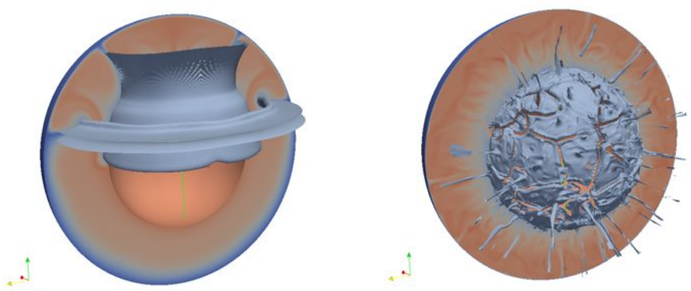

Figure 5. 3D sections of models with iso-surfaces showing cold, downwelling material for degree-1 mantle overturn (left) and shorter-wavelength, multiple instability overturn (right).

Table 2. Summary of model parameters distinguishing the degree-1mode of overturn and the multiple shorter-wavelength instability mode.

Mode of Mantle Overturn	Degree-1	Multiple, short-wavelength instabilities
Rayleigh Number	8e5	6e8
Reference Viscosity	1e24	1e21
Internal Heating	4	100
Half Space Age	500	50
Timesteps	1000	6000
Activation Energy	23.03	18.07
Temperature Offset	1	0.35

DISCUSSION & CONCLUSIONS

Our initial results show that catastrophic resurfacing can occur at Rayleigh numbers of the order of 10^5 with a yield stress of the order of 20-400 MPa, consistent with the results of van Heck and Tackley [15]. We see that the degree-1 mode of mantle overturn yields a smoother geoid with a larger range of variation than does the multiple, shorter-wavelength mode of mantle overturn. Also, the degree-1 mode of mantle overturn yields a smoother topography with a smaller range of variation than does the multiple, shorter-wavelength mode of mantle overturn. Because the modeled Venus data (Figure 1) manifests a shorter-wavelength, higher degree geoid and topography, we conclude that the shorter-wavelength, multiple instability mode of mantle overturn appears to be more relevant than does the degree-1 mode of mantle overturn.

We aim to compare the two modes of mantle overturn with the same mantle parameters in future calculations. Additionally, future work will include:

- systematically increasing the Rayleigh number in order to map out the behavior of mantle overturn as a function of Rayleigh number and yield stress
- assess the role of phase transformations and depth-increasing viscosity
- determine under what conditions resurfacing occurs as a single, global event and as several smaller-scale regional events closely spaced in time
- analyze whether these two cases can be distinguished using the model geoid, topography, and heat- flow after the overturn events by examining if, and how long, the signature of cold 'subducted' material in the deep mantle remains observable in the geoid, topography and heat flow
- determine whether we can generate stable plume structures consistent with known surface topography, geoid, and thermal emissivity data, as well as estimate the amount of melt produced by global resurfacing events
- determine whether volcanic resurfacing and lithospheric overturn can coexist in tandem or are in fact mutually exclusive mechanisms.

References: [1] Strom R. G. et al. (1994) *JGR*, 99, 10,899-10,926. [2] Herrick R. R. et al. (1997) *Venus II: University of Arizona Press*, 1015-1046. [3] McKinnon W. B. et al. (1997) *Venus II: University of Arizona Press*, 969-1014. [4] Hauck S. A. et al. (1998) *JGR*, 103(E6), 13,635-13,642. [5] Phillips R. J. et al. (1991) *Science*, 252, 651-658. [6] Phillips R. J. et al. (1992) *JGR*, 97, 15,923-15,948. [7] Schaber G. G. et al. (1992) *JGR*, 97, 13,256-13,301. [8] Turcotte D. L. (1993) *JGR*, 98, 17,061-17,068. [9] Turcotte D. L. (1995) *JGR*, 100, 16,931-16,940. [10] Turcotte D. L. (1996) *JGR*, 101, 4765-4773. [11] Turcotte D. L. et al. (1999) *Icarus*, 139, 49-54.; [12] Romeo I. and Turcotte D. L. (2010) *Planetary and Space Science*, 58, 1374-1380. [13] Smrekar S. E. et al. (2010) *Science, 328,* 605-608. [14] Reese C. C. et al. (1999) *Icarus*, 139, 67-80. [15] van Heck H. J. and Tackley P. J. (2008) *Geophysical Research Letters*, 35, doi:10.1029/2008GL035190. [16] Wieczorek M.A. (2006) *Treatise on Geophysics*, 30, 1-33.

Acknowledgements: Supported by grant NNX13AM87G from NASA Planetary Geology and Geophysics.