The Evolution of Surprisingly Stationary Plumes within Venus

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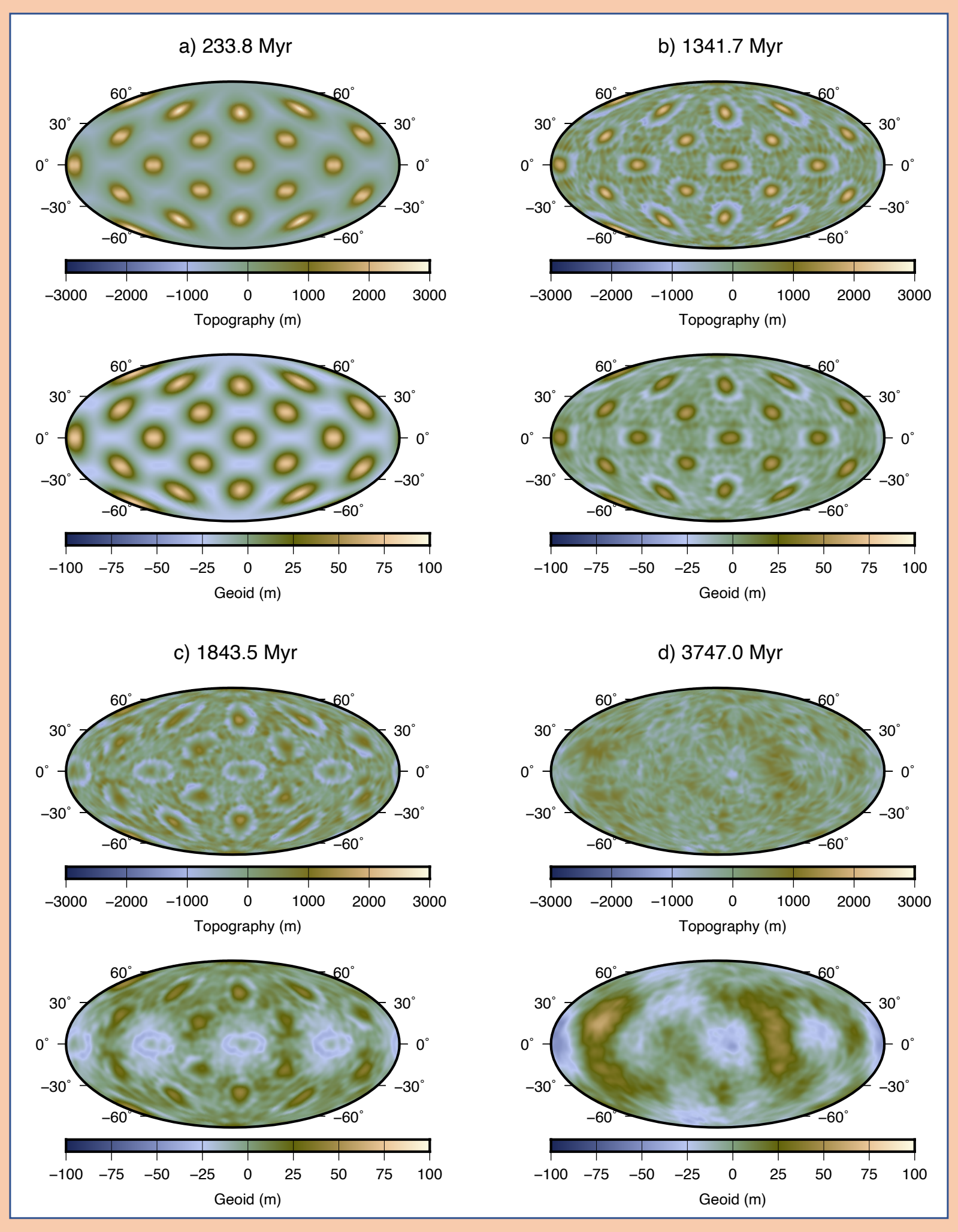
What are surprisingly stationary plumes?

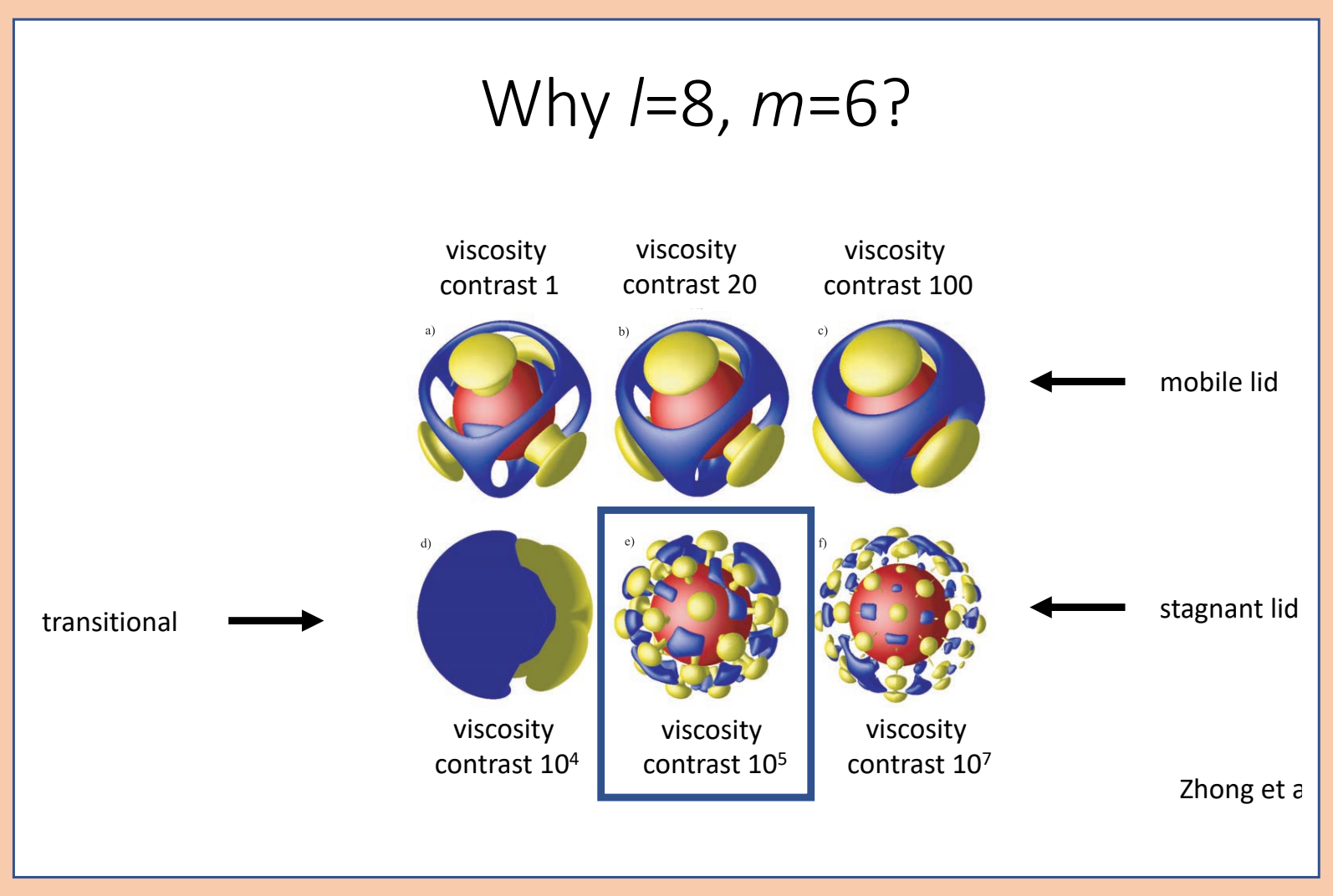
In many stagnant lid geodynamic models, when we start from short wavelength perturbations, the calculations quickly evolve into a regular, organized, pattern of plumes, remaining in a stable pattern for > 2 Gyr. This pattern clearly visible in the geoid and dynamic topography plots on the right.

The calculations are time-dependent and there are numerous small-scale 'drips' from the lithosphere that complicate identifying these plumes within the model; however they are prominent in the geoid because the plumes are vertical and continuous. The geoid integrates the temperature (density) as a function of depth, amplifying contributions continuous vertical structures- sort of like stacking in seismic imaging.

The pattern of surprisingly stable plumes can be represented by spherical harmonic degree 8 and order 6, a stable configuration for convection in spherical shells at low Rayleigh number (e.g., Busse, 1975). The combination of strong internal heating and most of the temperature contrast being sequestered in the stagnant lid makes internally heated stagnant-lid planets act more like low-Rayleigh number systems.



Why *l*=8, *m*=6?



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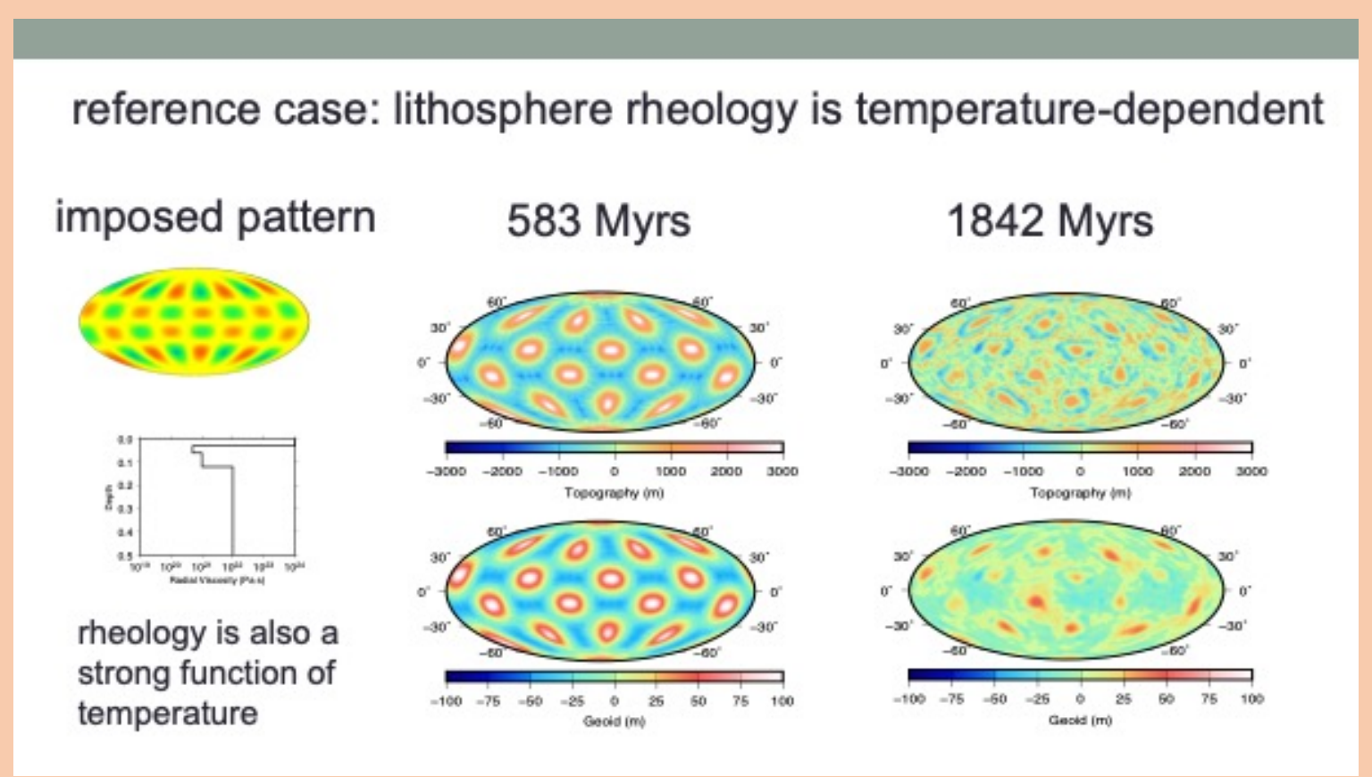
So what makes these plumes stationary?

The lithosphere plays an important role in this process. The initial rising plume head thins the lithosphere thinning the lithosphere. The concavity in the lithosphere stabilizes the plume. If we implement a rheology that is only pressure (or depth) dependent, then the plume stability breaks down much earlier in the calculation.

temperature-dependent rheology lid

depth-dependent rheology lid



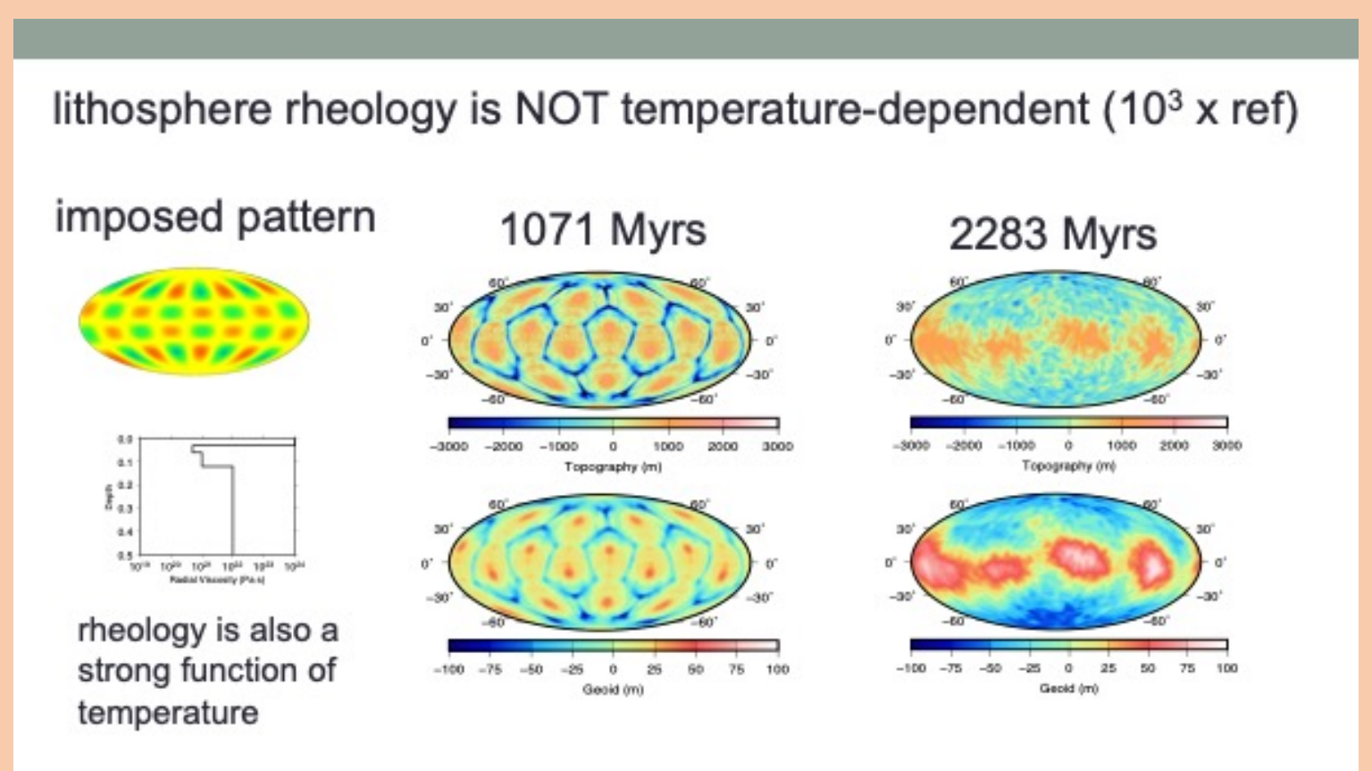
reference case: lithosphere rheology is temperature-dependent

imposed pattern

583 Myrs

1842 Myrs

rheology is also a strong function of temperature



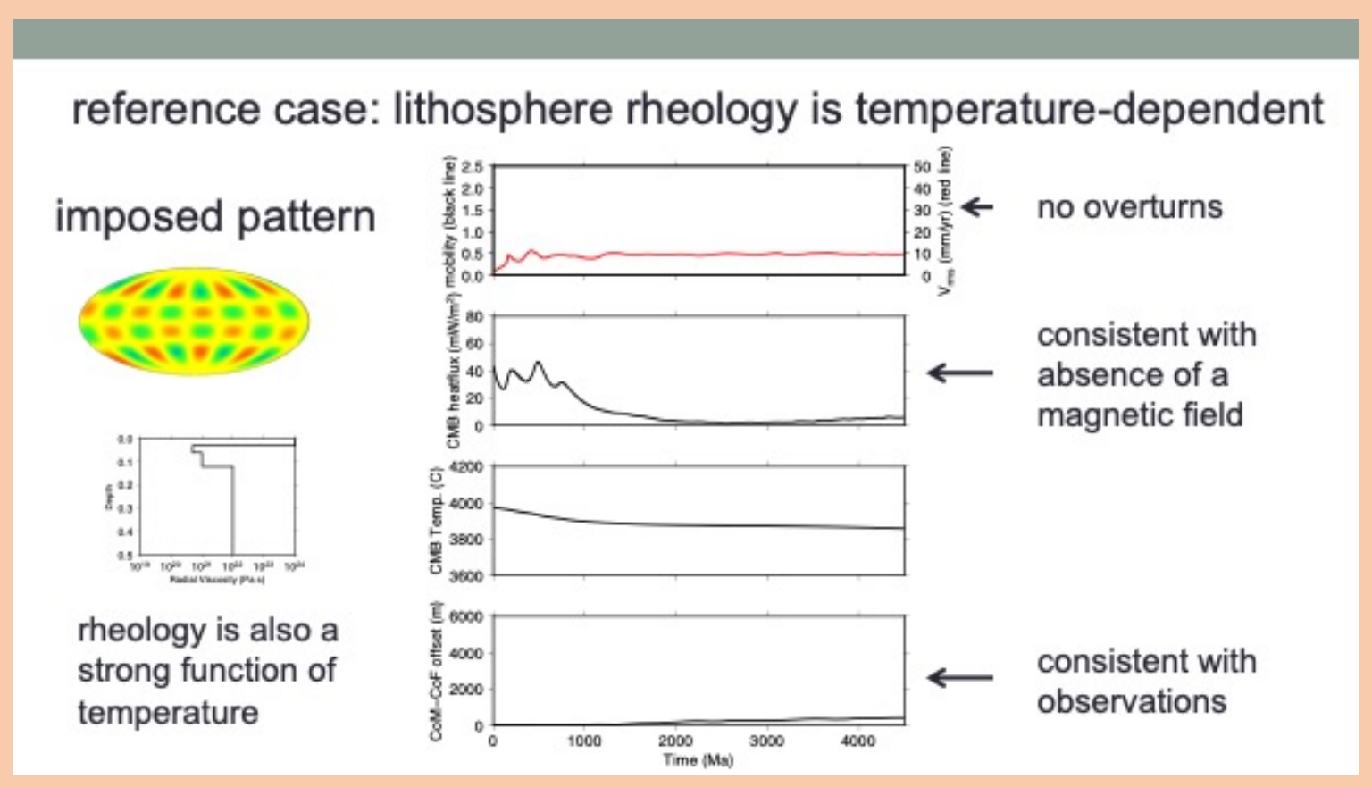
lithosphere rheology is NOT temperature-dependent (10^3 x ref)

imposed pattern

1071 Myrs

2283 Myrs

rheology is also a strong function of temperature



reference case: lithosphere rheology is temperature-dependent

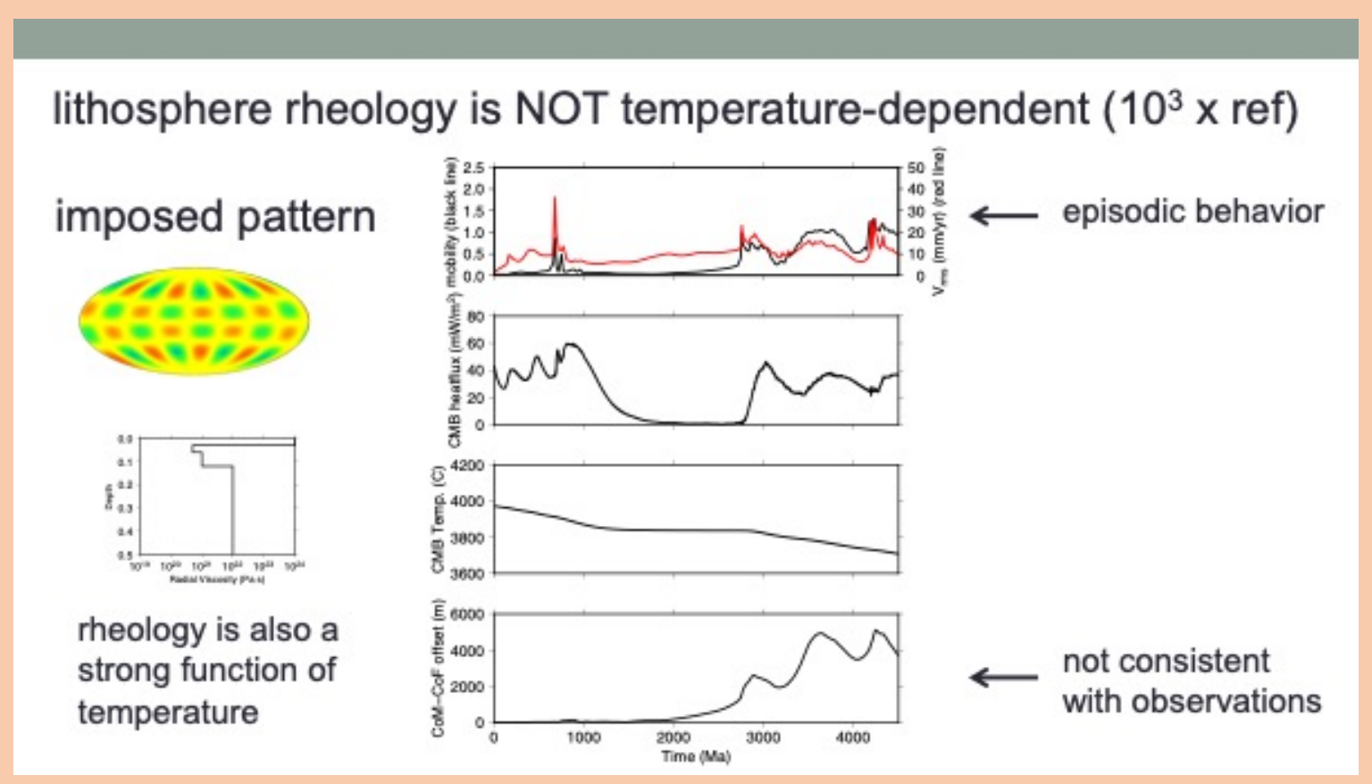
imposed pattern

no overturns

consistent with absence of a magnetic field

consistent with observations

rheology is also a strong function of temperature



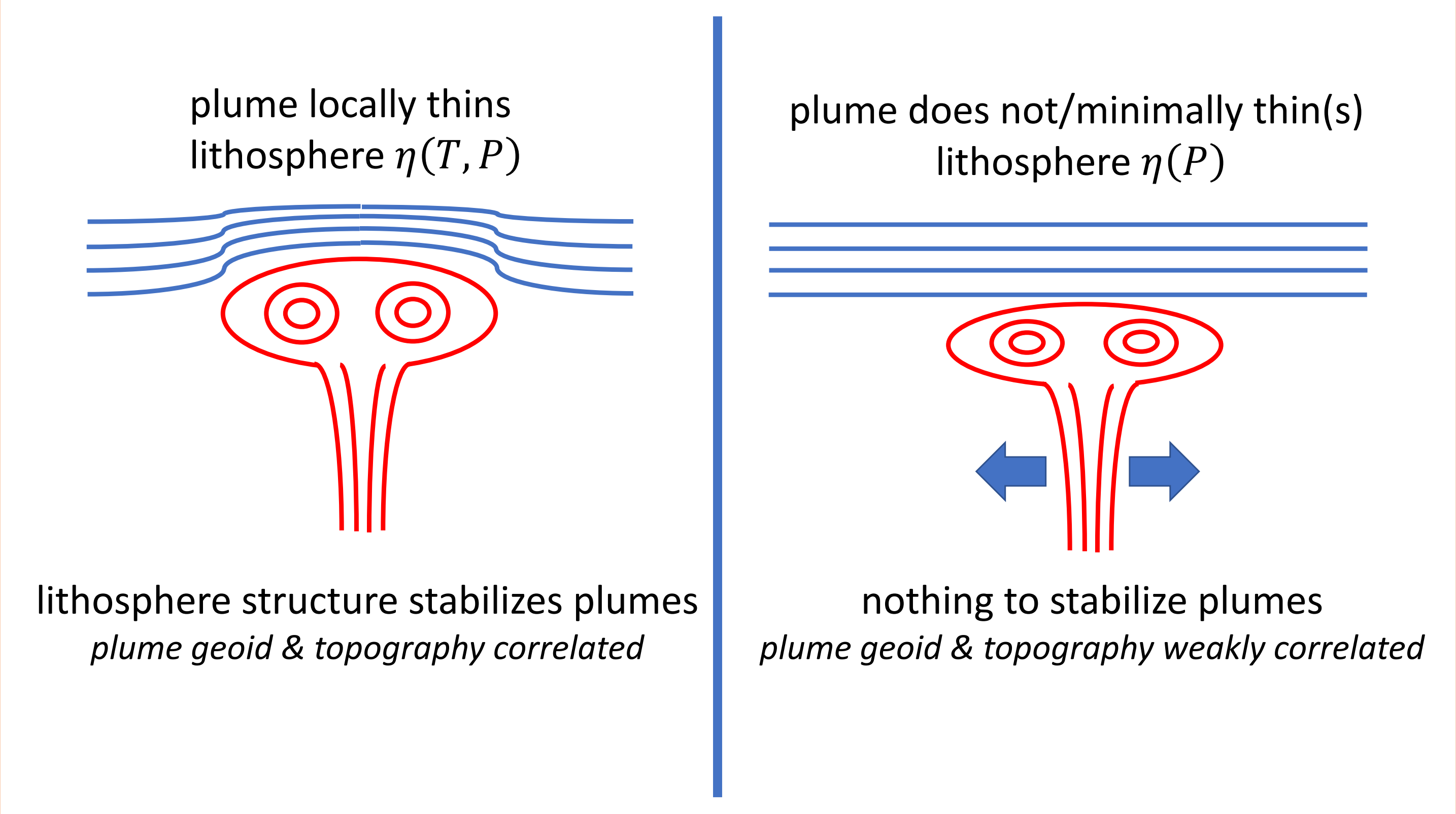
lithosphere rheology is NOT temperature-dependent (10^3 x ref)

imposed pattern

episodic behavior

not consistent with observations

rheology is also a strong function of temperature



plume locally thins lithosphere $\eta(T,P)$

lithosphere structure stabilizes plumes
plume geoid & topography correlated

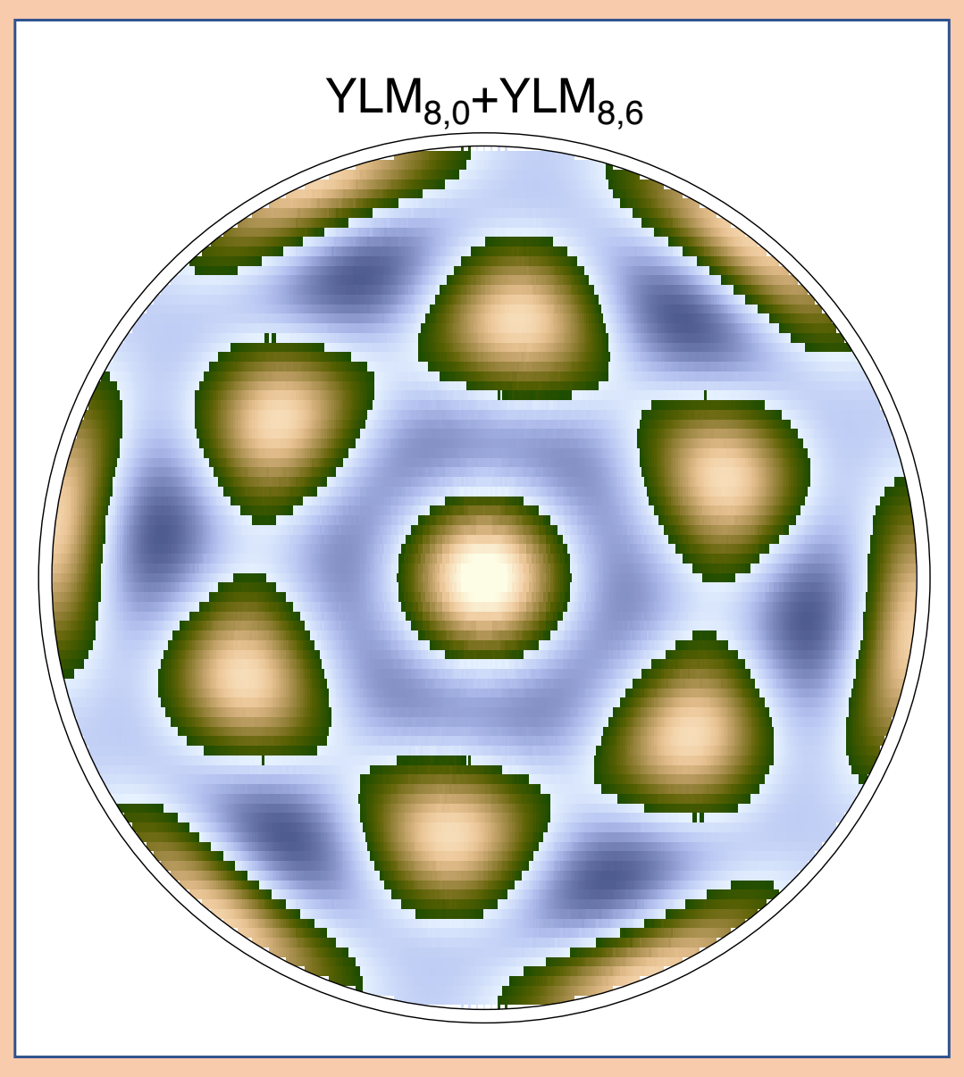
plume does not/minimally thin(s) lithosphere $\eta(P)$

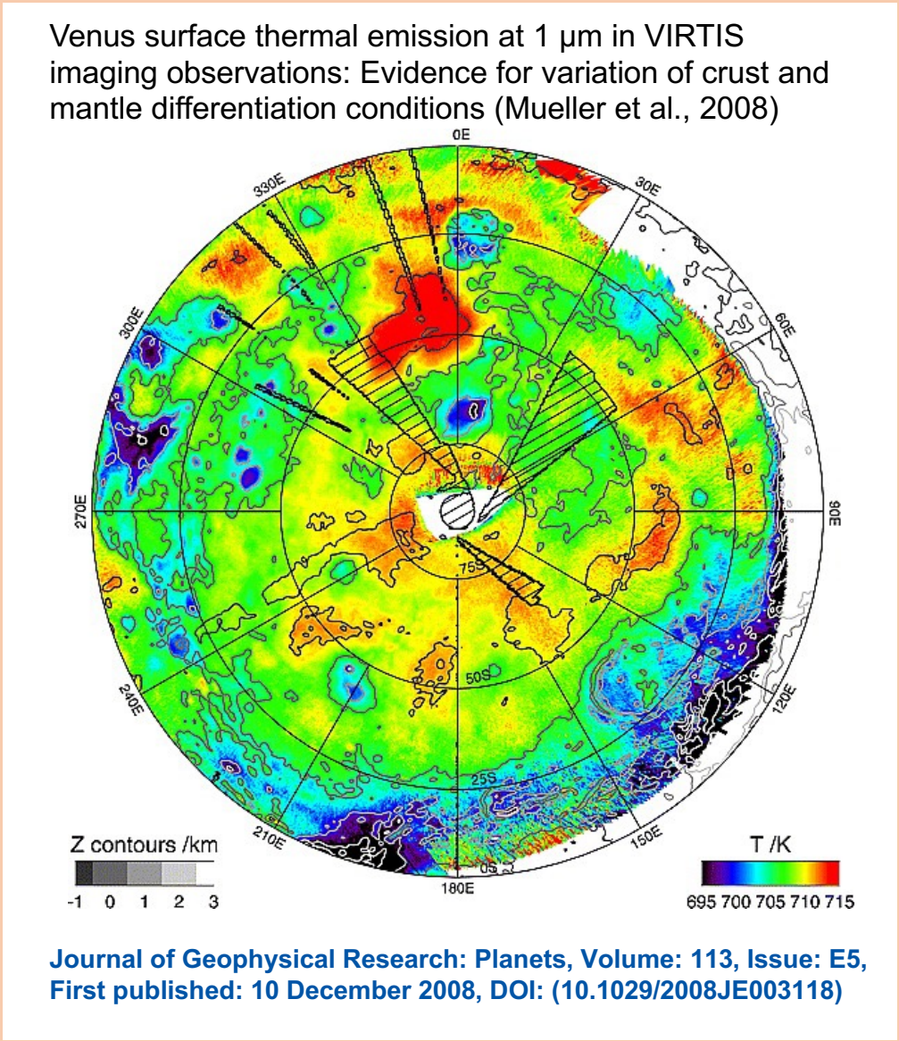
nothing to stabilize plumes
plume geoid & topography weakly correlated

While the fluid dynamic aficionado may remember that for a spherical shell appropriate for Venus' mantle, degree 4 is the first unstable mode for temperature-dependent rheology, it seems that at higher Rayleigh numbers there is a bifurcation to the degree 8 planform. Also, we have not found a study on the stability of strongly internally heated spherical shells, which is likely more the case for planets. Often stability analyses are performed with respect to a conductive initial condition which isn't the most appropriate stating point for planets, as they accreted hot.

But I study Venus, why should I care?

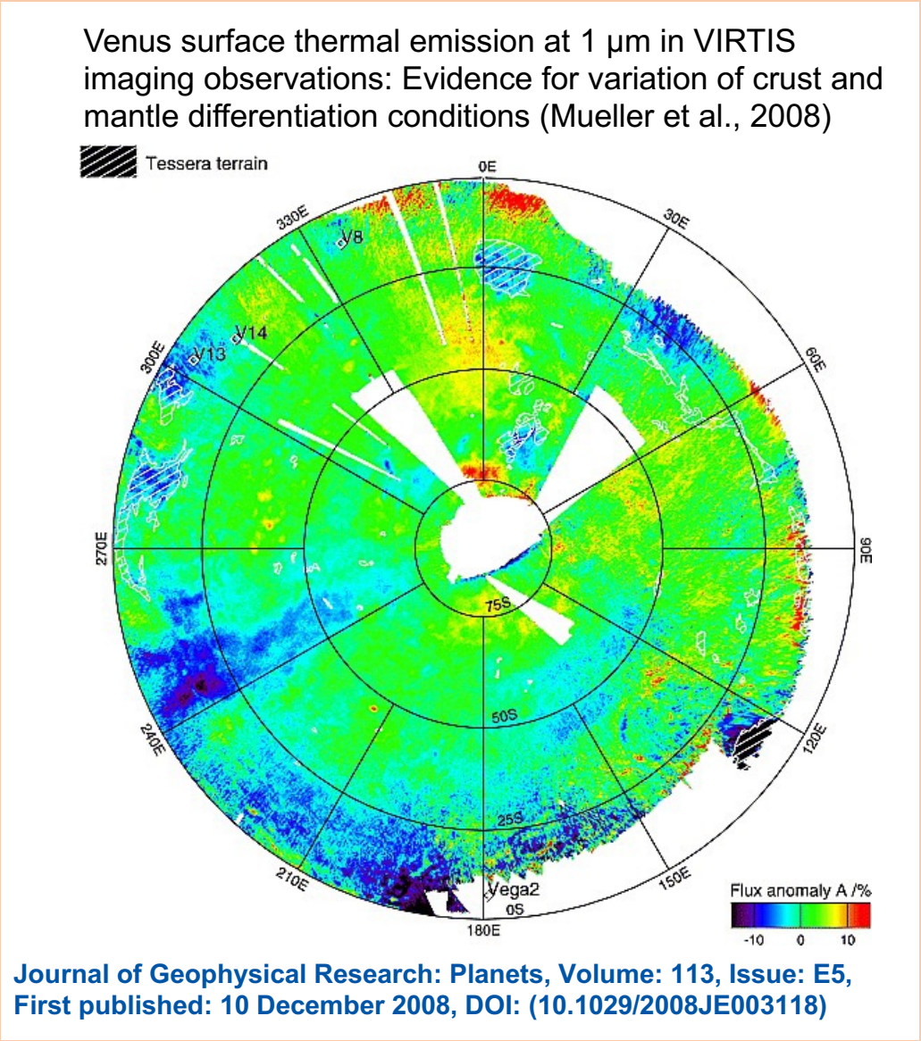
- mantle dynamics controls Venus' surface tectonics
  - surprisingly stationary plumes inhibit lithosphere overturn
  - power in low-degree harmonics of the gravity field (*l*=3, or center of mass/center of figure offset) may indicate a prior lithosphere instability event
- mantle dynamics controls Venus' volcanism
  - surprisingly stationary plumes favor continuous volcanic resurfacing
  - volcanic surfacing/thermal emissivity should retain an *l*=8,*m*=6 pattern (left) with 1 µm VIRTIS derived T (center) or flux anomaly (right)





Venus surface thermal emission at 1 µm in VIRTIS imaging observations: Evidence for variation of crust and mantle differentiation conditions (Mueller et al., 2008)

Journal of Geophysical Research: Planets, Volume: 113, Issue: E5, First published: 10 December 2008, DOI: (10.1029/2008JE003118)



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- keys to Venus' evolution may be buried deep in the mantle
  - power in low-degree harmonics of the gravity field (*l*=3, or center of mass/center of figure offset) may indicate a prior lithosphere instability event

Geeking out about the details

For those who are interested and/or worry about such things, we use a temperature-dependent rheology with yield strength criterion so that the lithosphere can become unstable, overturning and resurfacing. In cases where surprisingly stable plumes form this doesn't happen due to the high degree of symmetry in the pattern of plumes. If we start with a strongly anti-symmetric initial perturbation (e.g., spherical harmonic degree 1 or 3), the system evolves into a stagnant/mobile pattern.

We also use internal heat sources based on chondritic abundances of elements (e.g., McDonough and Sun, 1995). While it is likely that LIL elements (including U, Th, and K) are enriched in the crust, with our limited constraints any enrichment would be a guess. We also use a thermal evolution model approach to the core thermodynamics to allow for a cooling core boundary condition (King, 2018).

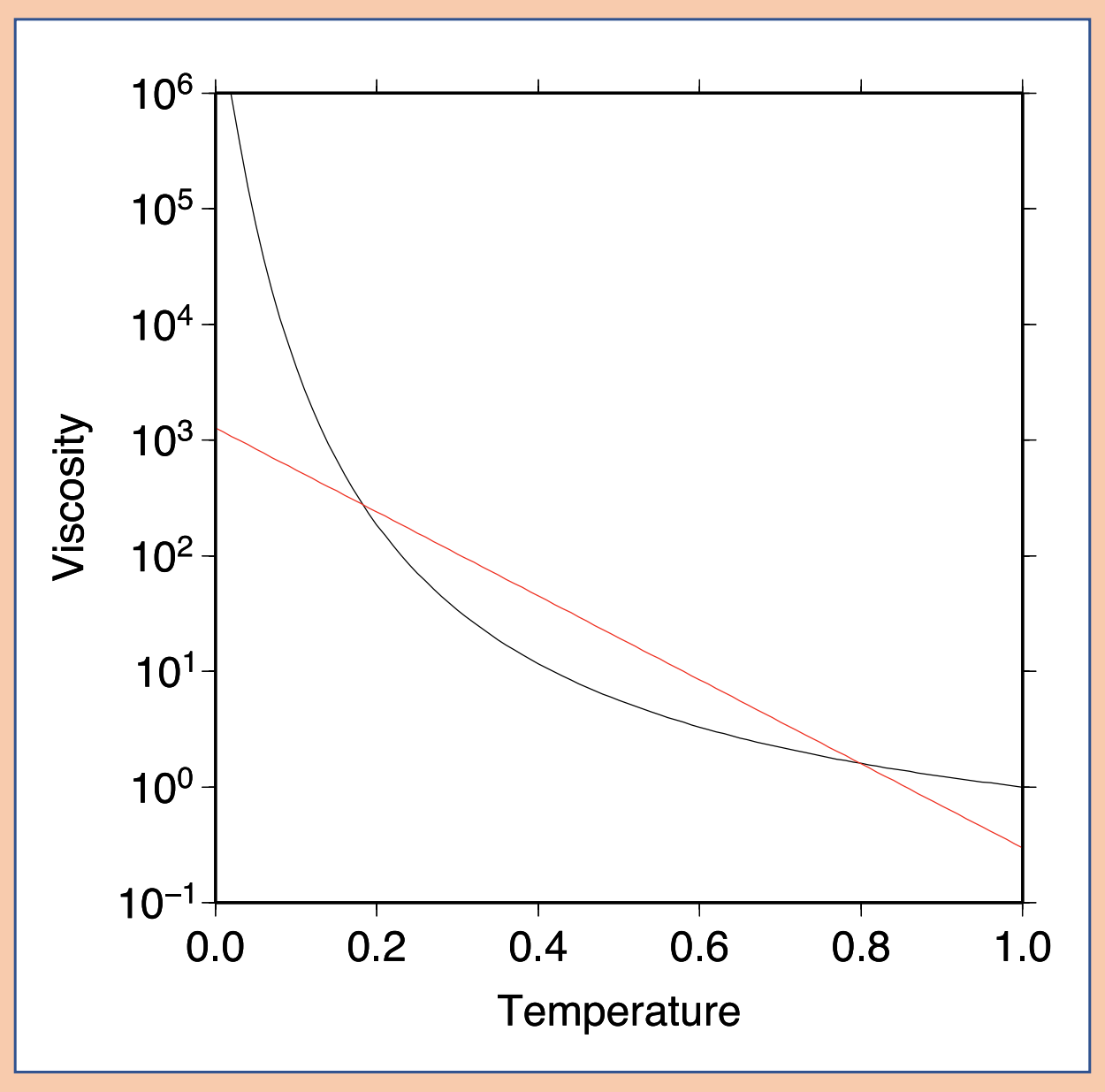
We use an Arrhenius form of the temperature-dependence and this turns out to be important. In the figure below, the viscosity profile from an Arrhenius viscosity formulation is shown in black compared with a viscosity profile from a Frank-Kamenetskii formulation shown in red. The Frank-Kamenetskii parameters are chosen to give the best match to the Nusselt number and RMS velocity from the Arrhenius viscosity formulation (King, 2009). The point is that in the Arrhenius form, the lithosphere viscosity is much larger than the lithosphere viscosity in the corresponding Frank-Kamenetskii form. Experimental rheology fit lab data to an Arrhenius NOT a Frank-Kamenetskii form. Studies that use a Frank-Kamenetskii rheology have far more frequent overturns than our studies. An Arrhenius rheology requires larger stresses to break the lithosphere because it is so much stronger.

Arrhenius form (black line):

$$\eta(T,P) = \eta_o \exp\left[\frac{E^* + PV^*}{RT} - \frac{E^* + PV^*}{RT_B},\right]$$

Frank-Kamenetskii form (red line):

$$\eta(T) = \eta_o \exp[-\beta(T - T_i)],$$



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