EPSC Abstracts
Vol. 12, EPSC2018-215-1, 2018
European Planetary Science Congress 2018

Inferences on the mantle viscosity structure and the post-overturn evolutionary state of Venus

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Abstract

Surface observations such as gravity, topography and surface age constrain the vastly unknown evolution of our neighbor Venus, but interpreting these signals requires advanced understanding of the surface-interior coupling and thus the dynamics of Venus' mantle and lithosphere. We investigate the generation of such observables from interior dynamics using numerical models of mantle convection. We find that Venus' present surface gravity spectrum is matched best with a mantle viscosity profile featuring a sublithospheric minimum of ~2x10^{20} Pas and a factor-100 gradual increase down to the deepest mantle, without a pronounced discontinuity around the mantle transition zone. This holds true for both stagnant-lid and episodic-lid regimes of convection. Overturns perturb the surface gravity spectrum and material recycled during the resurfacing annihilates the developed plume pattern in the mantle, which takes 1 Gyr or more to recover. Under substantial on-going volcanism, overturn scenarios limit crustal thickness to more reasonable values than stagnant-lid scenarios.

1. Introduction

Earth and Venus have evolved clearly differently - with plate tectonics operating on Earth, but not on Venus. Rather little is known about Venus' interior, but key for improvement is to use geophysical observables and infer their link to interior dynamics.

For Venus, powerful data are given by its gravity and topography whose long-wavelength components are sensitive to the deep interior, in particular radial viscosity variations [1], which in turn determine internal dynamics. Those constraints are typically non-unique, but this can be partly overcome by using additional constraints like the pattern of thermal emissivity anomalies, which may be related to Venus' pattern of mantle plumes [2].

We extract these constrains from our models and infer feasible mantle viscosity structures for present Venus. We use the mantle convection code StagYY [3] and incorporate complexities such as core-mantle coupling, phase transitions and melting [4].

2. Results

Unlike Earth, Venus' recent evolution has not been shaped by the continuous operation of plate tectonics at its surface. Presently, Venus is in a stagnant-lid regime of convection, but in its history the planet may have seen episodes of surface mobilisation and recycling (overturns). We thus discuss results for both stagnant-lid and episodic-lid evolutions.

Stagnant-lid cases: In this class of models, we vary rheological parameters governing mantle viscosity structure - the reference viscosity, the activation volume and the viscosity jump across the mantle transition zone. In summary, profiles with sublithospheric viscosity of ~2x10^{20} Pas and ~100x higher deep mantle viscosity match the gravity and topography constraints qualitatively best, at least at long-wavelength. In such cases the number of mantle plumes (~10) also compares well to the pattern of surface thermal emissivity anomalies detected on Venus [2]. In stagnant-lid, the number of plumes decays only slowly over time scales determined by mantle viscosity. Gravity and topography constraints moreover suggest a smooth viscosity increase without pronounced jump across the transition zone [1] as this corrupts the observed high correlation of topography and gravity.

On-going magmatism in these evolutions leads to basaltic crust at the top of the mantle, whose thickness exceeds the basalt-eclogite transition. This induces large lithospheric stress and should trigger failure, which is however prevented in the stagnant-lid models. As a result, crustal thickness grows to more than 150 km, well beyond other estimates.

Episodic-lid cases: We recompute the best matching stagnant-lid case, but now allow the lithosphere to fail (i.e. overturns can occur). Here, we focus on how an overturn affects surface observables such as the gravity power spectrum. The model is very sensitive to the yield stress of the lithosphere, but over some range (~40-70 MPa) evolutions with isolated, clearly distinguishable overturns are observed. When considering overturns, average crustal thickness is limited to more plausible values, but still relatively large (~50 km).

The recycling of surface material induces large density anomalies across the mantle. These perturb the predicted gravity and topography spectra. Ultimately, the recycled material accumulates on top of the core-mantle boundary (CMB) before vanishing via thermal diffusion and remixing. After overturn cessation, the remaining recycled material above the core does not affect the surface gravity spectrum strongly on long time scales (> 200 Myr). Once the perturbation fades, the episodic models lead to an even better match to the observational constraints than the stagnant-lid cases using the same rheological parameters, in particular at the longest wavelengths (spherical harmonic degrees L=2-3, Fig.1)

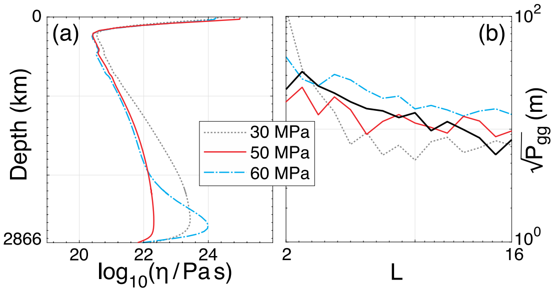

Fig. 1: (a) Averaged present-day mantle viscosity profiles from 3 episodic-lid cases with varying lithospheric yield strength, (b) corresponding surface gravity spectra P_{gg} for spherical harmonic range $2 \leq L \leq 16$.

Interaction of recycled surface material with the CMB also causes annihilation of the pre-overturn mantle flow structure. Mantle plumes are temporarily weakened or shut down, because the lower mantle boundary layer reinitializes following the accumulation of recycled material on top of the CMB. In our models, recovery from such an overturn perturbation takes up to 1 Gyr and more.

3. Discussion and Conclusions

Our 3D models of Venus' interior evolution qualitatively predict the observed gravity spectrum and its relation to topography as well as the number of mantle plumes if sublithospheric mantle viscosity is ~$2\text{x}10^{20}$ Pas and deep mantle viscosity is ~100x higher. A pronounced viscosity discontinuity across the mantle transition zone as on Earth seems unlikely, which may be linked to lower upper mantle water content on Venus compared to Earth.

Overturn events perturb the predicted gravity spectra and the pattern of mantle plumes within the mantle. After an overturn, recovery to a plume pattern in line with thermal emissivity constraints requires 1 Gyr or more in our models. However, the detailed link between mantle plumes and Venus' thermal emissivity anomalies remains not well understood yet. The surface gravity spectrum relaxes much faster from an overturn than the plume pattern (within 200 Myr): the observed spectrum may thus be a good representation of the stagnant-lid regime and is unlikely contaminated by remains of a previous overturn unless it ended only very recently.

Acknowledgements

We received funding from the Norwegian Research Council through a Centre of Excellence grant to the Centre for Earth Evolution and Dynamics (CEED, 223272). Computations were done on Stallo, a Notur facility, under project code nn9283. The authors thank P. J. Tackley for providing the code StagYY.

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