Introduction: Earth and Venus are often referred to as twin planets because of their similar radius and bulk density. However, their evolution has been clearly different - with plate tectonics operating on Earth, but not on Venus. Rather little is known about Venus’ interior, but key for improvement is to use available geophysical observations and infer their link to interior dynamics.

One powerful dataset is the Venustian gravity field whose long-wavelength components are sensitive to deep interior structure, in particular radial changes in viscosity [1,2], which in turn determines dynamics and evolution. Gravity constraints are non-unique, but we aim here to combine them with other constraints such as topography, the number of thermal emissivity anomalies [3] or surface ages [4] to reveal some features of Venus’ interior structure.

Methodology: Several studies recently aimed to reproduce gravity observations from mantle dynamics [1,5], but omitted evolutionary processes like magmatic activity and episodic overturns, with the exception of the 2D study of [6]. Using the mantle convection code StagYY [7], we incorporate secular cooling, core-mantle coupling, magmatic activity and episodic overturns in our model and investigate the evolution of Venus’ mantle and lithosphere through time and its relation to present-day observables.

Results: Mantle convection may be classified in different regimes [8]: mobile lid (plate tectonics), stagnant lid, and a transitional regime featuring episodic overturns. There is no evidence for a continuous mobile lid on Venus, but both other regimes may be relevant for its evolution - the episodic lid in particular with regards to its young and uniform surface age [4]. We thus separate our results into stagnant lid and episodic lid cases.

Stagnant lid cases: Using infinite yield stress (i.e. lithosphere cannot undergo plastic failure), the entire evolution is in the stagnant-lid regime. We vary rheological parameters governing viscosity structure, specifically the reference mantle viscosity (η₀), the activation volume (Vₐ) and the viscosity jump (Δη) across the mantle transition zone. These models are evaluated based on the predicted present-day gravity spectrum as well as the spectral correlation and the ratio of gravity and topography (GTR).

At long-wavelength, viscosity profiles with sublithospheric viscosity η₉L≈2x10²⁰ Pas and ~100x higher deep mantle viscosity match these constraints qualitatively best, although some differences to the observations remain. Note that η₀ is not a fixed input parameter, but a result of the planetary evolution with specified values for η₀, Vₐ, and Δη (see e.g. Figure 1).

Our preference is a smooth viscosity increase with depth, without pronounced jump across the transition zone [1,5], since large Δη corrupts the observed high correlation of topography and gravity. However, the absolute values of upper and lower mantle viscosity seem to be more important and reasonable matches between model prediction and observation can still be found if the viscosity increase with depth includes a (gentle) step across the transition zone.

We estimate the number of mantle plumes in the models. For our preferred case at present-day (η₀ = 1x10²¹ Pas, Vₐ=3.5x10⁻⁶ m³ mol⁻¹, Δη=1), we infer 9-10 plumes in good agreement with thermal emissivity constraints [3]. In stagnant-lid mode, this number seems fairly robust through time, but somewhat dependent on the details of detection.

All models show magmatic activity and thus surface renewal by eruption of basaltic magmas until present-day, in line with Venus dominantly basaltic crust. Magmatic activity peaks between ~3.0-2.5 Ga when mantle temperature is maximum. However, we find radiogenic heating of the interior to be the dominant contribution to the heat budget throughout the entire evolution, somewhat in contrast to previous 2D compressible stagnant-lid models [6].

One issue with the stagnant lid cases is that following the initial mantle overturn, magmatic activity in the upper mantle is very strong, which leads to several provinces of very thick basaltic crust over
the rising mantle plumes, significantly thicker than the basalt-eclogite transition depth. The density contrast associated with this transition generates large stresses in the lithosphere and should induce an overturn episode. However, this is not accounted for in these cases and the basaltic crust can only thin by convective erosion at its base. This process depends on upper mantle viscosity, but is generally slow and even after the whole evolution until present-day the resulting average crustal thickness seems very large (>150 km).

**Episodic lid cases:** We use the parameters of the best matching stagnant-lid case and re-compute its evolution with different finite yield stresses of the lithosphere. Note that our goal here is not to infer the controls on strength, duration or frequency of the overtures, but to study the effects of a single overturn with regards to observables available for Venus.

Using too low yield stress, overtures are frequent, which leads to more efficient cooling, thus higher viscosities and convective stresses. Eventually, this leads to a continuous mobile lid, which is not relevant for the scope of our study. The system is very sensitive to the yield stress, but over a small range of values (~50-60 MPa) evolutions with only two overtures can be observed of which the last one occurs the later, the higher the yield stress is.

Considering overturns, the extremely thick crustal provinces observed in the stagnant-lid cases are not observed, because the lithosphere fails under the high stresses that are induced if too much basaltic crust transitions to eclogite. Generally, this limits present-day values of average crustal thickness to more plausible values (~50 km).

Upon overturn and the sinking of cold surface material, large density anomalies are present across a wide range of depths, which strongly perturb the predicted gravity spectra and the relation to topography. However, with the assumed viscosity and density structure sinking speeds are rather high and recycled material quickly reaches the core-mantle boundary and accumulates there before disappearing mostly via thermal diffusion. After the overturn has ceased, the remains of such recycled material just above the core do not affect the surface gravity spectra strongly on long time scales (>200 Myrs).

Further effects of the arrival of cold recycled material at the core-mantle boundary are a peak in heat flux from the core into the mantle and strong perturbation of the flow structure before the onset of the overturn: the number of detected plumes changes significantly, because the lower mantle boundary layer has to reinitialize and reorganize following the overturn. Finally, the overturn induces a peak in magmatic activity and magmatic heat flux dominates the heat budget during this time, consistent with [6].

**Discussion:** Our 3D models of Venus’ interior evolution are capable of qualitatively predicting the observed spectra of surface gravity and its relation to topography as well as the number of mantle plumes assuming a stagnant-lid mode of mantle convection throughout the entire evolution if sublithospheric mantle viscosity is $\eta_l \sim 2 \times 10^{20}$ Pas and deep mantle viscosities ~100x higher. No strong viscosity discontinuity is favored, although a small jump cannot be excluded. We speculate, that a lower viscosity jump than inferred for Earth could be linked to different water contents in the upper mantles of Earth and Venus: Venus’ may be drier than Earth’s, where the transition zone includes a significant water [9], which could explain a viscosity reduction.

Overturn events strongly perturb the predicted spectra and number of hotspots in Venus’ mantle and may be necessary to avoid provinces of very thick basalt crust with a dense eclogitic base. After the overturn, recovery to a reasonable number of plumes as inferred from thermal emissivity observations seems to require a rather long time. However, the link between mantle plumes and thermal emissivity anomalies [3] is not well understood yet. The more reliable observable of surface gravity relaxes much faster from the overturn (< 200 Myrs). Venus present-day gravity spectrum should thus represent the stagnant-lid regime of its evolution and is probably not contaminated by any remains of a previous overturn unless the last overturn ended only very recently (< 200 Myrs ago). We currently analyze model-predicted surface ages to further discuss this issue.


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