THERMAL EVOLUTION, MAGMATIC STYLE, AND TIDAL DEFORMATION OF VENUS. Thomas Vaujour[1,2], Ana-Catalina Plesa[1], Michaela Walterova[1], Doris Breuer[1] [1]German Aerospace Center, Institute of Planetary Research, Berlin (ana.plesa@dlr.de), [2]German Aerospace Center, Institute of Planetary Research, Berlin, and ISAE-SUPAERO, Toulouse (thomas.vaujour@student.isae-supaero.fr).

Introduction: Although similar to the Earth in size and mass, Venus represents today one of the most extreme places in the Solar System having a dense CO2 atmosphere and a young surface covered by volcanic features. While it is still debated whether in its early history Venus might have had more similar surface conditions to the Earth, i.e., a similar surface temperature and perhaps surface water [1], it is beyond doubt that volcanism has played a major role in the planet's evolution.

Whether Venus has been in a stagnant lid regime during its entire history is not yet established. The so-called tessera plateaus, whose composition has been suggested to be silica rich, more similar to that of the Earth's continents [3], would require for their formation some form of crustal recycling during the past, potentially resembling subduction processes on Earth [4].

In this study we present thermo-chemical evolution models of Venus and take into account the effects of magmatism on the interior dynamics. We test thermal histories for purely stagnant lid models and for models in which surface mobilization takes place during the evolution. In all simulations we calculate the mechanical lithosphere thickness that can be compared with current estimates of the elastic lithosphere thickness. In addition, we compute the tidal parameters and the present-day eruption rate. All these output quantities that are predicted by our geodynamical models will be constrained by future observations of the VERITAS and EnVision missions [5, 6].

Numerical Model: We use the mantle convection code Gaia-v2 [7] to model the thermal evolution of Venus in a 2D spherical annulus geometry. The models include a pressure- and temperature-dependent thermal conductivity and expansivity [8] and consider core cooling and decay of radioactive heat sources.

Melt that is produced in the mantle is instantaneously extracted at the surface, but can also remain trapped in the lithosphere or crust. Since the ratio of extrusive to intrusive magmatism (*e/i* ratio) is poorly constrained, we varied this between 0 (fully intrusive) to 1 (fully extrusive) in steps of 0.1. Another poorly constrained parameter is the depth of the intrusive melt, which we vary in our models between 10 km and 80 km in steps of 5 km.

The P-T dependent mantle viscosity follows an Arrhenius law. In our models we test three different reference viscosity values (1e20, 1e21, and 1e22 Pa s). While a reference viscosity of 1e20 Pa s indicates a slightly wet/iron-rich mantle, 1e22 Pa s represents an extreme value for a dry mantle rheology with a low FeO abundance. Our simulations include both stagnant lid and surface mobilization cases.

Finally to compute the tidal deformation, we use a semi-analytical model based on the normal mode theory for radially stratified viscoelastic bodies [9]. The model uses pre-computed mineralogy tables and an Andrade rheology, and is coupled to the thermal evolution models through the mantle viscosity.

Results and Discussion: Based on the thermal state of the interior of Venus that is obtained in our simulations, we calculate the mechanical thickness at present day using a strength envelope formalism [10]. The thinnest mechanical thickness is obtained for models with an intrusive depth deeper than 40 km and an *e/i* ratio smaller than 20%. For larger amounts of extrusive melt and for a shallower intrusive depth, the mechanical thickness increases due to the efficient cooling of the lithosphere by the cold lithospheric material that is pushed when melt is extracted from the mantle. We observe a mechanical thickness about two to three times thicker for reference viscosities of 1e21 Pa s and 1e22 Pa s compared to 1e20 Pa s.

In Fig. 1a we present a summary of the cases that use a reference viscosity of 1e20 Pa s and show with diamond symbols simulations, for which the intrusive melt remains trapped at the base of the crust or within the crust, using crustal thickness estimates from [11]. Assuming a dry rheology and requiring that the mechanical thickness should not exceed 60 km (plus symbols in Fig. 1) in order to be compatible with the elastic lithosphere thickness estimates [12], our results suggest that at most 50% of the melt will reach the surface and the present-day eruption rate lies below 6 km^3/yr (Fig. 1b).

The cases presented in Fig. 1 assume that Venus has been in a stagnant lid convection mode throughout its thermal history. However, Venus might have experienced episodes of surface mobilization in the past. Nevertheless, these episodes of surface mobilization might have occured at least ~350 Myr ago, since a too recent surface mobilization event has been found incompatible with the surface gravity spectrum [13].

In Fig. 2 we show the effects of surface mobilization

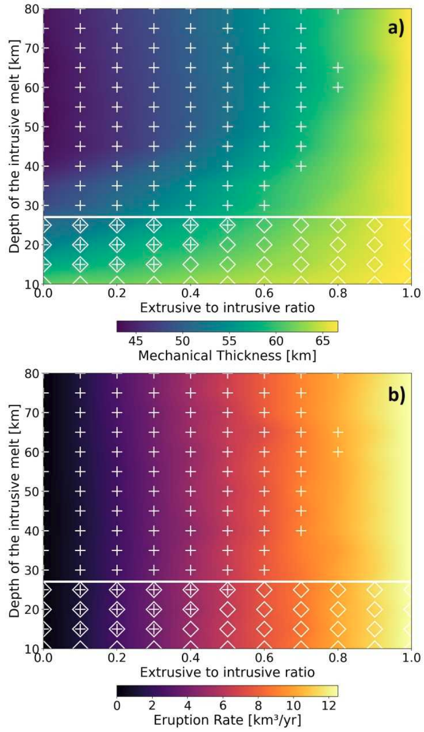

Figure 1: a) mechanical thickness calculated using a strength envelope formalism and assuming a dry rhology; b) eruption rates calculated from the numerical models. The horizontal line shows the maximum crustal thickness estimate of Venus [11]. The plus symbols show mechanical thickness values compatible with elastic thickness estimates. Pluses and diamond symbols show the cases where the melt remains trapped at the base of the crust or within the crust.

on the evolution and present-day distribution of the mechanical thickness for a case assuming an intrusive melt depth of 20 km and an *e/i* ratio of 0.2. Two strong surface mobilization events take place at around 500 Myr and 1500 Myr. After about 2500 Myr the average mechanical thickness for the surface mobilization and the stagnant lid case is very similar, with slightly smaller mechanical thicknesses in the surface mobilization case that are caused by much smaller resurfacing events and foundering of the stagnant lid, similar to the so-called squishy lid regime [14]. The present-day eruption rates found for such surface mobilization cases are similar to the stagnant lid models.

The tidal deformation values obtained in our models reflect the sensitivity of the tidal parameters to the present-day thermal state, since in all geodynamic models, the core size was set to 3025 km. In all simulations, high k_2 and low Q values are obtained for a large *e/i* ratio and/or shallow intrusions. For a reference viscosity η_{ref}=1e22 Pa s we obtain a k_2 of 0.289±0.0034, for η_{ref}=1e21 Pa s the tidal Love number k_2 is 0.273±0.0051, and for η_{ref}=1e20 Pa s we obtain k_2 of 0.262±0.0014. The tidal quality factor Q is sensitive primarily to the mantle rheology, and in our models, we obtain values of 25±2 for a reference viscosity η_{ref}=1e22 Pa s, 42±7 for η_{ref}=1e21 Pa s, and 67±5 for η_{ref}=1e20 Pa s.

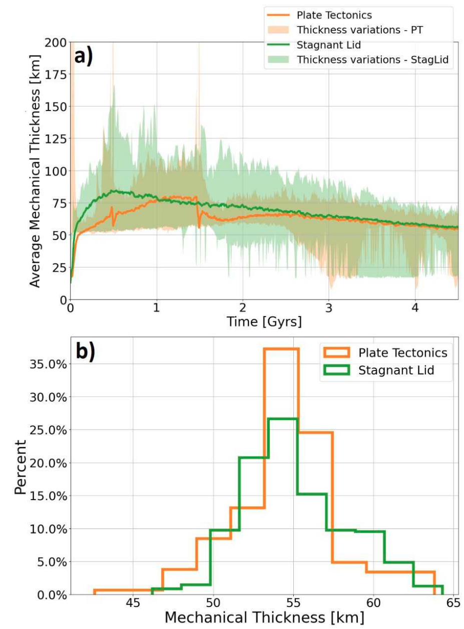

Figure 2: a) mechanical thickness evolution for a stagnant lid and a surface mobilization case; b) histogram of the mechanical thickness values calculated at present-day.

Conclusions: Our preliminary study shows that assuming a dry mantle, present-day eruption rates and *e/i* ratio can be constrained. A wet mantle rheology for the mechanical thickness calculation, however, would allow for fully extrusive melt and two times higher eruption rates. For episodic mantle convection, the results are similar under the assumption that the last resurfacing event occurred at least about 350 Myr ago.

The mantle rheology and the magmatic style could be constrained by the tidal parameters, for which estimates will be derived from future measurements of the VERITAS and EnVision missions [5,6]. Moreover, these missions will search for active volcanic and tectonic activity on Venus that could help to distinguish between the thermal evolution models proposed in this study.

References: [1] Way et al., *GRL* (2016); [2] Gillmore et al., *SSR* (2017); [3] Smrekar et al., *SSR* (218); [4] Resor et al., *JGR* (2021); [5] Ghail et al. AAS/Division for Planet. Sci. (2016); [6] Smrekar et al., EPSC (2020); [7] Hüttig et al. *PEPI* (2013); [8] Tosi et al., *PEPI* (2013); [9] Sabadini & Vermeersen, Kluwer Academic Publishers (2004); [10] McNutt, *JGR* (1984); [11] James et al., *JGR* (2013); [12] O'Rourke & Smrekar, *JGR* (2018); [13] Rolf et al., *Icarus, 313* (2018); [14] Lourenço et al., *G3, 21* (2020).