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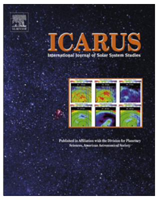

Lithospheric structure of Venus from gravity and topography

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ABSTRACT

There are many fundamental and unanswered questions on the structure and evolution of the venusian lithosphere, which are key issues for understanding Venus in the context of the origin and evolution of the terrestrial planets. Here we investigate the lithospheric structure of Venus by calculating its crustal and effective elastic thicknesses (T_c and T_e, respectively) from an analysis of gravity and topography, in order to improve our knowledge of the large scale and long-term mechanical behaviour of its lithosphere. We find that the venusian crust is usually 20–25 km thick with thicker crust under the highlands. Our effective elastic thickness values range between 14 km (corresponding to the minimum resolvable T_e value) and 94 km, but are dominated by low to moderate values. T_e variations deduced from our model could represent regional variations in the cooling history of the lithosphere and/or mantle processes with limited surface manifestation. The crustal plateaus are near-isostatically compensated, consistent with a thin elastic lithosphere, showing a thickened crust beneath them, whereas the lowlands exhibit higher T_e values, maybe indicating a cooler lithosphere than that when the venusian highlands were emplaced. The large volcanic rises show a complex signature, with a broad range of T_e and internal load fraction (F) values. Finally, our results also reveal a significant contribution of the upper mantle to the strength of the lithosphere in many regions.

1. Introduction

Venus and the Earth share a similar size, nearly equivalent density and bulk composition, and close proximity to the Sun. Despite these similarities, Venus's tectonics and dynamic evolution are very different from those of the Earth. The venusian lithosphere is stagnant and shows no evidence for present-day global plate tectonics (e.g., Solomon and Head, 1982; Solomon et al., 1992). Recent data provided from the Venus Express Mission show evidence of geologically young, and even ongoing, volcanism on the venusian surface (Smrekar et al., 2010). However, the thermal history of Venus remains an enigma and there are many fundamental and unanswered questions on the structure and evolution of its lithosphere (e.g., Smrekar et al., 1997; Stofan et al., 1997; Phillips et al., 1997; Grimm and Hess, 1997), which are key issues for understanding Venus in the context of the origin and evolution of the terrestrial planets (Garvin et al., 2009; Ghail et al., 2012; Sotin et al., 2014; VEXAG, 2014).

The analysis of gravity and topography data provides useful constraints to solve many fundamental questions on the geodynamics of terrestrial planets, probing the structure and mechanical behaviour of their lithospheres, for example how they respond to loading and unloading (Wieczorek, 2007; Audet, 2011, 2014; Watts et al., 2013). In particular, a useful parameter that describes this behaviour is the effective elastic thickness (T_e) of the lithosphere, which, in turn, can be used to constrain the thermal structure and evolution of a planetary body (e.g., Zuber et al., 2000; McGovern et al., 2002; Ruiz et al., 2011). T_e is a proxy for the strength of the lithosphere, integrating contributions from brittle and ductile layers and from elastic cores of the lithosphere (for a review see Watts and Burov, 2003).

Although previous research provided important constraints on the effective elastic thickness of Venus (e.g., Johnson and Sandwell, 1994; Smrekar, 1994; Simons et al., 1994, 1997; McKenzie and Nimmo, 1997; Smrekar and Stofan, 1999; Barnett et al., 2000, 2002; Hoogenboom et al., 2004, 2005), work on global mapping of T_e is very scarce. Anderson and Smrekar (2006) presented the first global map of T_e for Venus based on the spatio-spectral localization technique of Simons et al. (1997) by using three end-member models of loading (top loading, bottom loading, or hot spot) and fitting their results to specified classes

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of results. Recently, Audet (2014) used a spherical wavelet analysis of gravity and topography and thin shell loading models, and presented preliminary mappings of T_e for the Moon, Mars and Venus, in order to analyse both the promises and the limitations of fully spherical techniques.

Recent advances in joint spectral analysis of gravity and topography and improvements in lithospheric modelling of the Earth have led to mapping of T_e at an unprecedented resolution (for reviews see Audet, 2014; Kirby, 2014). Given these recent methods developed for the Earth, it is a natural step to make a reliable T_e map for Venus at high resolution. Performing this task would be of interest to re-evaluate regional variations in, and improve the characterization of, the structure and rheological behaviour of the lithosphere of this planet.

Thus, we have calculated maps of the spatial variations of venusian T_e, as well as of their associated surface and subsurface loading mechanisms, from the analysis of the Bouguer coherence using a wavelet transform (Kirby and Swain, 2009, 2011), modelled with a simple thin elastic plate subject to both surface and subsurface loads, following the load deconvolution procedure of Forsyth (1985). We have performed our mapping in the Cartesian domain, dividing the surface of Venus into 36 overlapping areas (or 'tiles'). This procedure is useful: indeed, the radius of curvature of Venus is large enough for the elastic plate and shell formulations to produce equivalent coherence spectra for the expected range of T_e values (see Audet, 2014). Also, Audet (2014) showed that the Cartesian analysis is robust over small regions if the data edges of the Cartesian grid are excluded. Prior to estimating T_e, we present a global model of crustal thickness, which is required for the lithospheric analysis, derived from topography and gravity. Finally, we discuss the implications of our results for the large scale and long-term evolution and behaviour of the venusian crust and lithosphere.

2. Global gravity and topography of Venus

Gravity and topography data acquired by the Magellan spacecraft between 1990 and 1994 remain the most complete set for constraining the structure of the venusian lithosphere. We apply potential theory to model the crustal thickness of Venus from the relationship between gravity and topography data (Section 3). This analysis has been developed in spherical coordinates making use of spherical harmonics. Thus, we use the spherical harmonic models SHTJV360u (Rappaport et al., 1999) and SHGJ180u (Konopliv et al., 1999) for topography and gravity respectively (available at http://pds-geosciences.wustl.edu; see Fig. 1).

While SHTJV360u and SHGJ180u are supplied to degree and order 360 and 180, respectively, the topography and gravity used in spectral flexural analyses must have the same bandwidth, because the coherence (and admittance) compares these data in the spectral domain. Therefore we expand the gravity and topography coefficients up to degree and order 180 only, which corresponds to a minimum wavelength of ≈211 km at the venusian equator. This corresponds to a flexural wavelength such that the minimum resolvable T_e is ≈14 km (estimated through $\lambda_{flex} \approx 29T_e^{3/4}$; see Swain and Kirby, 2003), which is useful taking into account the limited data resolution and large errors in the gravity model (see Audet, 2014). However, we note that the accuracy of the SHGJ180u gravity data is quite low, with large uncertainties at spherical harmonics beyond 60–70 (see for example, Anderson and Smrekar, 2006; Wieczorek, 2007; James et al., 2013); we will return to this issue in Section 5.

Effective elastic thickness modelling has been developed in the Cartesian domain by using a continuous planar wavelet analysis of gravity and topography data (see Section 4). Although Audet (2011, 2014) recently developed a continuous spherical wavelet transform for estimating T_e, he found that the differences between the spherical and planar methods were small (<10% of the absolute T_e value) for Earth-size planets and concentrated at the data area edges (Audet, 2014). In order to reduce the effects of distortion from curvature of a planet's surface, we divide the surface of Venus into 36 overlapping areas (or 'tiles') from north to south and west to east (Fig. 2a), and project the gravity and topography in each of them to a Cartesian frame using an oblique Mercator map projection, providing a global coverage. Each tile has dimensions of 6000 km (easting) × 6000 km (northing), and a grid spacing of 20 km in both directions. The Bouguer gravity anomaly and topography are mirrored about their edges prior to Fourier transformation with the purpose of reducing leakage, which, when used with the wavelet transform, does not generally bias the results significantly (see Kirby and Swain, 2008, for a discussion on mirroring). The planar wavelet analysis for coherence and subsequent inversion for T_e were then carried out on each tile. Inversions for T_e and subsurface-to-surface load ratio (f; see Section 4) were performed only on observed coherences with wavelengths >211 km (accordingly, both gravity and topography data were truncated to degree and order 180 in our analysis; see above). After inversion, T_e and F data at the edges of each tile (10% of a side length) were removed to mitigate possible remnant edge effects near the grid boundaries (see Fig. 2b). As a final step, T_e and F results were back-projected onto geographic 1° × 1° grids, and merged and gridded using GMT's 'surface' algorithm (Smith and Wessel, 1990) to produce global T_e and F maps that combine the information from all tiles.

All maps are generated using GMT (Wessel et al., 2013), and are presented in Robinson projection with east-positive longitude convention and centred on 180° longitude.

3. Crustal thickness modelling

We use the relationship between global topography and gravity data to model the crustal thickness (T_c) of Venus following the potential theory procedure of Wieczorek and Phillips (1998), which was originally derived for estimating T_c of the Moon and later used in other crustal thickness modelling of the Moon (Wieczorek, 2007), Mars (Zuber et al., 2000; Neumann et al., 2004; Wieczorek, 2007; Cheung and King, 2014), and Venus (Wieczorek, 2007; James et al., 2013). To constrain the thickness of the venusian crust, we assume (1) that the observed gravitational anomalies arise only from a combination of surface topography and variations at the crust–mantle interface (i.e., the "Moho"), and (2) constant crustal and mantle densities to overcome the non-uniqueness associated with potential modelling. Under these assumptions, we first calculate the Bouguer gravity anomaly from surface topography and the free air anomaly, and then calculate by downward continuation the relief along the crust–mantle interface necessary to explain the observed Bouguer gravity anomaly (for reviews see Wieczorek and Phillips, 1998; Wieczorek, 2007). In order to mitigate errors in downward continuing the Bouguer anomaly, we applied a minimum amplitude filter (see Wieczorek and Phillips, 1998) for the Moho relief at degree $l = 70$. Finally, we obtain the crustal thickness by subtracting the relief on the Moho from surface topography.

Since we cannot constrain the crustal thickness model with a given value at a specific location on Venus (for example, by using the minimum T_c at deep impact basins as Hellas or Isidis on Mars; e.g., Neumann et al., 2004), we assume a mean T_c to "anchor" our model satisfying the condition that the inverted crustal thickness is not negative anywhere on the planet. Furthermore, the phase transition from basalt to dense eclogite limits large T_c values