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Separation of dynamic and isostatic components of the Venusian gravity and topography and determination of the crustal thickness of Venus

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ABSTRACT

Assuming that the long-wavelength geoid and topography of Venus are supported by both mantle convection and Airy isostasy, we propose a method to separate the dynamic and isostatic components of the Venusian gravity and topography with the aid of the dynamic admittance from numerical models of mantle convection and the isostatic admittance from an Airy isostatic model. The global crustal thickness is then calculated based on the isostatic component of the gravity and topography. The results show that some highland plateaus such as Ishtar Terra and Ovda Regio have thick crust, which are largely supported by isostatic compensation. Other highland plateaus such as Thetis and Phoebe Regiones appear to have superimposed contributions from crustal thickening and dynamic support. Volcanic rises such as Atla and Beta Regiones have thin crust, which is consistent with the postulation that these volcanic rises are mainly the products of dynamic uplift caused by mantle plumes.

1. Introduction

Mantle convection is the primary mechanism that controls the heat loss and evolution of the terrestrial planets such as the Earth and Venus. Although Venus and the Earth have similar size, density and composition, Venus lacks global plate tectonics in which the lithosphere is formed at mid-ocean ridges and subducts at trenches (Kaula and Phillips, 1981; Nimmo and McKenzie, 1998). Different from the Earth, mantle convection on Venus is dominated by several mantle plumes amidst an interconnected network of downwellings (Huang et al., 2013; Kiefer and Hager, 1991; Phillips and Hansen, 1998; Phillips et al., 1991; Smrekar and Sotin, 2012; Smrekar et al., 2010; Stofan et al., 1995). Our knowledge about Venus mainly comes from studies of radar images, gravity and topography obtained from space probes and known tectonics on the Earth.

On the basis of elevation, Venus's surface can be divided into highlands, plains and lowlands. Lowlands on Venus have negative gravity and geoid anomalies, and they are thought of as surface expressions of mantle downwellings (Bindschadler et al., 1992). Highlands on Venus can be further subdivided into volcanic rises and highland plateaus based on their different geology, topography and gravity (Phillips and Hansen, 1998; Smrekar and Phillips, 1991). Volcanic rises are dome-like, circular to elongate regions that have broad topography rises, large gravity anomalies, large geoid topography ratio (GTR) and large apparent depths of compensation (ADC) (Bindschadler et al., 1992; Phillips and Hansen, 1998; Stofan et al., 1995). Volcanic rises are identified as surface expressions of mantle plumes because the GTR and ADC are too large to be explained by crustal thickness variations alone (Smrekar and Phillips, 1991; Smrekar et al., 2010; Stofan et al., 1995). Highland plateaus are steep-sided, quasi-circular to irregular regions and they are thought to be isostatically compensated with thick crust as evidenced by their small gravity anomalies, low GTR and shallow ADC (Grimm, 1994; Phillips and Hansen, 1998; Simons et al., 1997; Smrekar and Phillips, 1991). Both models of upwelling and downwelling have been hypothesized for the formation of highland plateaus (Anderson and Smrekar, 2006; Bindschadler et al., 1992; Herrick et al., 1989; Phillips and Hansen, 1998; Phillips et al., 1991).

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The long-wavelength topography and geoid of Venus are believed to have a large dynamic component induced by the mantle (Herrick and Phillips, 1992; Huang et al., 2013; James et al., 2013; Kiefer et al., 1986; McKenzie, 1994; Pauer et al., 2006; Steinberger et al., 2010). It has been shown from the analysis of the global spherical harmonic spectra of the topography and geoid (i.e., gravity) data that they are highly correlated and show a relatively large ratio or admittance for degrees 2–40, which cannot be explained by simple Airy equilibrium or elastic plate model, suggesting a largely dynamic origin (Kiefer et al., 1986; Pauer et al., 2006; Simons et al., 1997). However, topography from numerical simulations of mantle convection with purely dynamic origin have difficulty in matching the observed topography (Huang et al., 2013). Huang et al. (2013) formulated three-dimensional global models of mantle convection to simultaneously explain the number of plumes and the spectra of surface topography and gravity for Venus. Their preferred model reproduces well the number of plumes and the geoid spectra, but its topography amplitude remains smaller than the observed. They suggested that it's because they have ignored the crust and crustal compensation process that produces the topography but negligible geoid anomalies at intermediate- and long-wavelengths for Venus.

The crust of Terrestrial planet forms from decompression melting when the mantle materials rise toward the surface. The crust is generally basaltic in composition, enriched in incompatible elements and possesses a relatively lower density than the mantle (Breuer and Moore, 2007; Nimmo and McKenzie, 1998). On the Earth, the crust has a strong ongoing secondary formation and can subduct, melt, and become part of the warm rising magma again. Unlike the Earth's crust, the present production of Venus's crust by partial melting is thought to be small as Venus lacks water to allow the rocky material to deform. The crust of Venus might have been replaced due to a global resurfacing event (Armann and Tackley, 2012; Nimmo and McKenzie, 1998). Studying the crustal thickness of Venus can yield important information about the tectonics of Venus's surface. The knowledge of Venus's crust is mainly from the interpretation of Venusian gravity and topography data. Since the Magellan spacecraft obtained the high-resolution data of the gravity and topography in the early 1990s, a lot of studies have been made. Several methods to determine the crustal thickness of Venus have been proposed: (1) Viscous relaxation model (Grimm and Solomon, 1988; Phillips and Hansen, 1994); (2) Global admittance modeling in the spectral domain (e.g., Pauer et al., 2006; Wieczorek, 2007); (3) Admittance modeling in the spatial domain (the GTR) (e.g., Kucinskas and Turcotte, 1994; Smrekar and Phillips, 1991; Wieczorek and Phillips, 1997; Wieczorek and Zuber, 2004); (4) Localized admittance analysis (e.g., Anderson and Smrekar, 2006; Simons et al., 1994; Simons et al., 1997); (5) Global crustal thickness inversion from modified Parker's formula in the spherical coordinate (e.g., Parker, 1972; Wei et al., 2014; Wieczorek, 2007; Wieczorek and Phillips, 1998).

Estimates of Venus's mean crustal thickness range from 15 km to 35 km (Breuer and Moore, 2007; Grimm and Solomon, 1988; James et al., 2013; Pauer et al., 2006; Simons et al., 1994; Wieczorek, 2007). Highland plateaus are thought to possess relatively large crustal thickness and to be compensated at depth (Grimm, 1994; Kucinskas and Turcotte, 1994; Simons et al., 1994, 1997; Smrekar and Phillips, 1991). Although it is widely accepted that volcanic rises are due to mantle plumes, the crustal structure of volcanic rises is debated. The large apparent depths of compensation found for these volcanic rises (Kucinskas and Turcotte, 1994; Smrekar and Phillips, 1991) cannot be thought of as due to the crustal thickness but imply dynamic support for these regions. Leftwich et al. (1999) concluded that the crust of Beta Regio is thickened and may exceed 40 km, and that the thickened crust was produced by volcanism as a result of large partial melting. Simons et al. (1994, 1997) suggested that the ADCs at volcanic rises are too large to be explained by crustal thickening and the present crust of Venus does not thicken or thin significantly in response to convective tractions. McKenzie (1994) argued that the crustal thicknesses of Atla and Beta Regiones are smaller than the average crustal thickness after eliminating the dynamic effect.

The dynamical influences on Venus need to be excluded from the observed gravity and topography data in order to obtain better estimates of crustal thickness. Based on the mantle convective platform of Venus, if we can determine which topography is dynamically supported and which topography is isostatically supported, much progress about the origin of these topography features can be made. Previous efforts for separating the dynamic component include simultaneously inverting for crustal thickness variations and mass anomalies in the mantle, thus separating the effects of shallow and deep compensation mechanisms on the topography and geoid (Herrick and Phillips, 1992; James et al., 2013), but the viscosity structure and loading depth required by their model are rather uncertain. McKenzie (1994) used a constant admittance of 50 mGal km^{-1} to subtract the dynamic topography, which neglected possible spatial variations of admittance. Another study for separating the dynamic component is Wei et al. (2014), which deducted the dynamic effect by using the spatial varied dynamical admittance from numerical models of mantle convection. however, their method cannot separate the dynamic and isostatic components of the gravity and topography simultaneously, and has to ignore the isostatic component of the gravity for degrees 2–40.

Here we assume that the long-wavelength (degrees 2–40) geoid and topography of Venus are supported by both mantle convection and Airy crustal compensation. We separate the dynamic and isostatic components of the gravity and topography from the observed data by using the mantle convection model's dynamic admittance and Airy model's isostatic admittance. Following this, we use the isostatic component of the gravity and topography to calculate the global crustal thickness of Venus by using the method of Wieczorek and Phillips (1998). Finally, we discuss the implications for the tectonics of Venus such as the origin of highland plateaus and the structures of volcanic rises.

2. Separation of dynamic and isostatic components of the Venusian gravity and topography

Venus's radial gravity anomaly Δg_r, geoid N and topography h can be expressed as a linear combination of spherical harmonics as (Wieczorek, 2007):

$$\Delta g_r = \frac{GM}{r^2}\sum_{n=2}^{\infty}\sum_{m=-n}^{n}\left(\frac{R_0}{r}\right)^n (n-1)C_{nm}Y_{nm}(\Omega) \tag{1}$$

$$N = R_0\sum_{n=2}^{\infty}\sum_{m=-n}^{n} C_{nm}Y_{nm}(\Omega) \tag{2}$$

$$h = R_0\sum_{n=0}^{\infty}\sum_{m=-n}^{n} h_{nm}Y_{nm}(\Omega) \tag{3}$$

where G is the gravitational constant, M is the total mass of Venus, r is distance, n is degree, m is order, R_0 is the reference radius, C_{nm} is the spherical harmonic coefficient of the gravity and geoid, h_{nm} is the spherical harmonic coefficient of the topography, Ω represents position on the sphere in terms of colatitudes θ and longitude φ, Y_{nm} is the spherical harmonic function of degree n and