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Evidence of mantle upwelling/downwelling and localized subduction on Venus from the body-force vector analysis

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ABSTRACT

Considering that Venus has a size very similar to Earth, thermal evolution of both planets should be comparable. Nonetheless, there is no clear evidence of plate tectonics or plate motions on Venus. Instead, various surface deformations attributed to volcanism, resurfacing, localized subduction and other geologic processes were recognized on the planet. In this study we attempt to classify the origin of lithospheric forces on Venus based on using topographic and gravity information. For this purpose, we also estimate the Venusian crustal thickness. In agreement with findings from previous studies, the signature of past or recent global tectonism in the body-force vector pattern on Venus is absent, while exhibiting only regional anomalies. The maximum intensity inferred in the Atla and Beta Regios is likely attributed to mantle upwelling. This is also confirmed by the gravity-topography spectral correlation and admittance analysis that shows the isostatic relaxation of these volcanic regions. The regional body-force pattern in the Bell Regio suggests that a much less pronounced force intensity there is possibly related to crustal load of lava flows. Elsewhere, the body-force intensity is relatively weak, with slightly more pronounced intensity around the Ishtar Terra and the Arthemis Chasmata. The body-force pattern in the Arthemis Chasmata supports the hypothesis that coronae structures are the result of mantle upwelling and the subsequent (localized) plume-induced subduction with only limited horizontal crustal motions. The prevailing divergent pattern of body-force vectors in the Ishtar Terra region suggests the presence of tensional forces due to the downwelling mantle flow that is responsible for a crustal thickening along the Freyja and Maxwell Montes. Except for the Atla and Beta Regios where the isostasy is relaxed by the (active) mantle plumes, the crustal thickness is spatially highly correlated with the topography, with a thin crust under the plains and a thick crust under the plateaus. The maximum Moho depth under the Maxwell Montes in the Ishtar Terra exceeds 90 km.

1. Introduction

A principal problem of interpreting surface deformations on Venus is the origin of large horizontal forces near the surface in the apparent absence of plate tectonics (e.g. Bindschadler et al., 1992). Different hypotheses have been proposed (see e.g. Basilevsky et al., 1986; Turcotte, 1993; Phillips and Hansen, 1994; Strom et al., 1994; Nimmo and Stevenson, 2000; Basilevsky and Head, 2000; Spohn, 2009; Smrekar et al., 2010; Davaille et al., 2017; and references therein) to explain the formation of the Venusian surface, involving catastrophic events, gradual formation and formation during different major geologic events.

To understand better the origin of large horizontal forces on Venus, in this study we used the topographic and gravity information to model the body forces and interpreted the results with respect to existing hypotheses about the formation of the Venusian surface. In the absence of seismic data, the method proposed by Runcorn (1967) and modified (for a variable crustal thickness) by Eshagh (2015) can be used. Tenzer et al. (2015) applied this method to investigate the body forces on Mars. They demonstrated that most of the Martian body-force intensity is attributed to crustal load of volcanic accumulations in the Tharsis region. This method was also applied to investigate the terrestrial body-force vector pattern induced by mantle convection; the overview of these studies can be found in Eshagh and Tenzer (2015). Here, we computed the global body-force vectors on Venus using this method and compared it with the

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result obtained by applying the method that relates the swell-push force to the geoid undulations (see e.g. Turcotte and Schubert, 2002). The computation of body-force vectors according to Eshagh's modification of Runcorn's theory requires the knowledge of a variable crustal thickness. In planetary studies, Airy's isostatic theory is typically used to estimate the Moho depth. Since Airy's theory assumes only a local compensation principle, we applied Vening Meinesz-Moritz's (VMM) regional isostatic principle (Sjöberg, 2009, 2013) to represent more realistically the actual responds of the lithosphere on the load. Moreover, in Airy's theory, the compensation depth is estimated based on considering a simple Bouguer plate to approximate the topography, while the isostatic compensation of crustal roots is estimated with the same simple approach by assuming an infinite compensation plate. Such approximate methods might yield large inaccuracies in values of the Bouguer gravity disturbances that could be eliminated by applying the topographic gravity correction computed according to the procedure developed and applied by Tenzer et al. (2009a; 2009b; 2012) that takes into account the real topographic geometry and density structure (if known). We expect that these numerical procedures could improve the interpretational quality of results used to study the lithospheric structure and processes. In particular, we used the results of gravimetric modelling of the crustal thickness and the body-force vectors to interpret major surface features on Venus, involving also the spatial and spectral analysis of the gravity and topographic models. We further focused on regional studies of volcanic rises (the Atla, Beta and Bell Regios), coronae (the Arthemis Chasmata) and the highest topographic formation (the Ishtar Terra). We then verified our major findings from gravimetric interpretations using existing geological hypotheses about the origin and evolution of these surface features.

2. Venusian geology and topography

The formation of the Venusian surface is attributed to three major geologic units, comprising the Fortunian, Guineverian and Atlian Periods. The geological map of Venus according to Ivanov and Head (2011) reclassified using a 1×1 arc-deg grid step is shown in Fig. 1. The topographic map of Venus is shown in Fig. 2. The topographic heights on Venus were generated on a 0.5×0.5 arc-deg grid with a spectral resolution complete to the spherical harmonic degree 180 using the VenusTopo719 digital terrain model (Wieczorek, 2007) derived from the Magellan, Pioneer Venus and Venera altimetric data. For a detailed description of major topographic features on Venus (see Fig. 3) and the geological evolution we refer readers to studies, for instance, by Bindschadler and Parmentier (1989), Solomon et al. (1992), Head et al. (1992), Phillips and Hansen (1994), Ansan et al. (1996), Wieczorek (2007), or Shalygin et al. (2012).

3. Venusian gravity field

We applied methods for a spherical harmonic analysis and synthesis of gravity and topographic models to compute the free-air and Bouguer gravity disturbances. All computations were realized globally on a 0.5×0.5 arc-deg grid with a spectral resolution complete to the spherical harmonic degree 180.

3.1. Gravity disturbances

The free-air gravity disturbances at the topographic surface were computed from the MGNP180U global gravity model (Konopliv et al., 1999) that was compiled based on processing the Magellan Doppler radiometric tracking data. As seen in Fig. 4, the free-air gravity disturbances are distributed mostly within ± 150 mGal, except for some localized large positive values over a highly elevated topography. This small interval of gravity values indicates that major topographic features on Venus are isostatically compensated. Negative values of the gravity disturbances are seen over the plains and moderately-elevated regions with gravity lows (to -167 mGal) along the Atalanta, Aino and Gulnevere Planitiae. Large positive gravity values are detected over the plateaus with maxima (up to 489 mGal) at the Maat Mons volcano. Large positive gravity disturbances are also seen over volcanic rises of the Atla, Beta, Bell, Eistla, Dione, Themis and Imdr Regios. Additional large positive gravity values are distributed over some coronae that are not necessarily elevated structures. These gravity highs support the hypothesis of a mantle plume forming the coronae. A more detailed discussion of this aspect is postponed until Section 7.

3.2. Geoid model

We used the newly developed method (Tenzer et al., 2018) to compute the geoidal heights from the spherical harmonics of external gravity field that takes into consideration the gravitational contribution of topography. Such procedure is necessary for the computation of

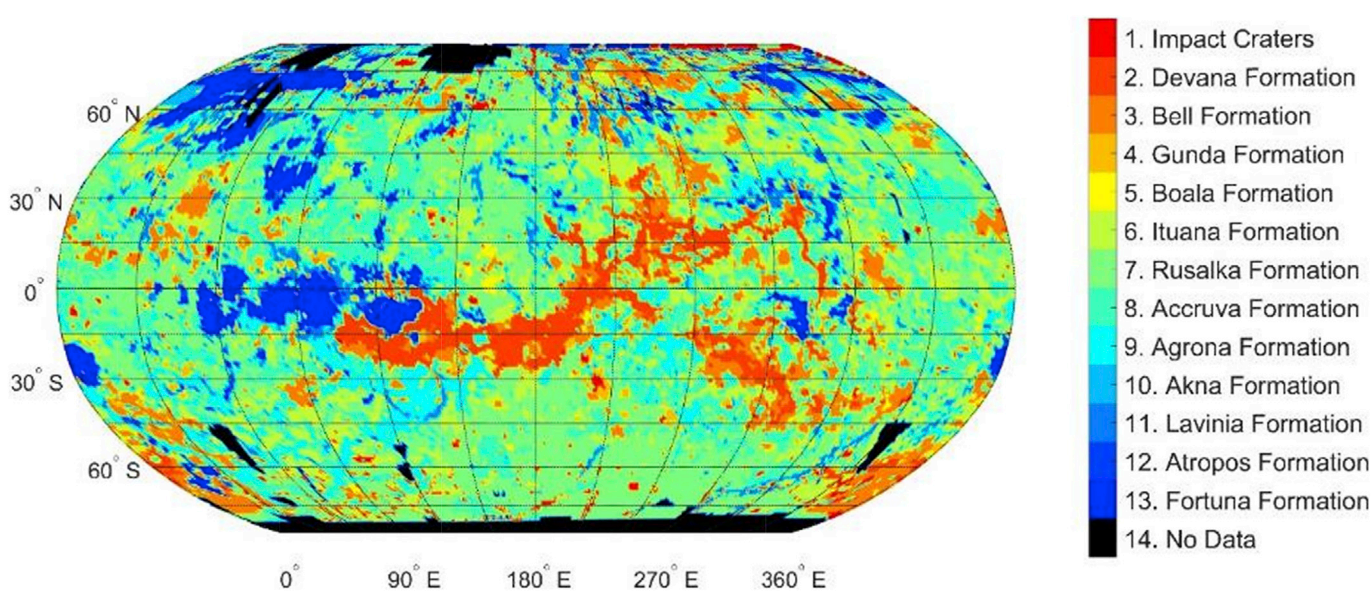

Fig. 1. Geological map of Venus according to Ivanov and Head (2011) reclassified using a 1×1 arc-deg grid step, showing major formations of Fortunian, Guineverian (Atropos, Lavinia, Akna, Agrona, Accruva, Rusalka and Ituana) and Atlian (Devana, Gunda and Boala) Periods.