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The Isostatic Stagnant Lid Approximation: Application to Venus

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Analysis of topography and gravity data is the most common, yet highly non-unique, way to determine the variations in the lithospheric thickness on planets. Perhaps, the simplest approach is based on the assumption of some form of isostasy. This is a very attractive assumption because it does not involve the poorly constrained mechanical properties and the dynamics of the mantle and the lithosphere. A number of papers have argued that the Venusian topography is likely to be supported isostatically, by either a single density variation at a depth of 100 km [1] or a distributed density variation over 1000 km depth [2]. Morgan and Phillips [3] used a model of a single lithospheric plate of global extent with a linear temperature profile to suggest that most of the Venusian topography can be explained by variations in lithospheric thickness. Smrekar and Phillips [4] used geoid to topography ratios determined from theoretical depths of isostatic compensation and concluded that regions with low ratios are likely to be a result of the thermal thinning of a 100 km thick lithosphere while regions with high ratios require some dynamic support. However, the latter conclusion was a consequence of the assumption that the Venusian lithosphere cannot be much thicker than on Earth. If this assumption is relaxed, a thicker lithosphere is considered the resulting thick lithosphere and its variations can produce higher geoid to topography ratios. Kucinskas and Turcotte [5] and Moore and Schubert [6] used a similar approach to analyze the data, but did not limit the lithospheric thickness by any Earth-based values. They applied the "HOT'" equation [7,8] to several isostasy models and found that the Venusian lithosphere is rather thick, up to about 300 km in some areas.

The assumption of thermal isostasy in these studies was largely motivated by the analysis of the terrestrial mid-ocean ridges whose structure almost perfectly fits the thermal isostasy models. However, it remained unclear if this assumption could be applied to Venus and if any dynamic support was required to explain at least some part of the gravity and topography signals as was suggested by Smrekar and Phillips. Early numerical simulations of mantle convection on Venus indicated that the thermal isostasy component associated with warm rising material was insignificant in comparison to the dynamic support provided by the advection of the rising material itself [9-12]. Kiefer et al. [13] showed that the long-wavelength gravity and topography anomalies (up to degree 18) were a result of dynamic support from mantle convection rather than Airy or Pratt isostasy. They determine this by showing that the admittance curve is fit reasonably well by a model with a 100 km thick high viscosity near-surface layer. Kiefer and Hager [14] then applied this model to the equatorial highlands of Venus and suggested that they were supported dynamically by rising mantle plumes. They stated that the dynamic support of these regions was required because the expected 60 km thick crust was far too thin for that expected for Airy isostasy. McKenzie [12] found that the observed topography and gravity agreed well with that calculated from the dynamic support in numerical models of rising plumes in constant viscosity fluids and argued that hot rising plumes are correlated with positive gravity anomalies and cold plumes with negative ones. These and other models (e.g. [13-17]) assume either constant or radially varying viscosity.

While the above models provided important insights into the planetary structure, they did not take into account lateral viscosity variations which were shown to be important in the interpretation of gravity and topography data [18]. Solomatov and Moresi [19] argued that strongly temperature-dependent viscosity convection can explain the large geoid to topography ratios through the thermal thinning of a thick viscous surface layer (stagnant lid) which forms naturally at large viscosity contrasts. This behavior cannot occur in models where the viscosity is constant or varies only radially. A recent analysis of the role of thermal isostasy in convective systems shows that most of the gravity and topography signals indeed can be explained almost entirely by thermal isostasy of the stagnant lid [20]. This suggests that thermal isostasy can be applied to certain regimes of convection, supporting the early interpretations of gravity and topography on Venus, and leads to basic assumption of the Isostatic Stagnant Lid (ISL) approximation for convective systems: the primary support mechanism for the long-wavelength topography in the stagnant lid regime of temperature-dependent viscosity convection is thermal isostasy of the stagnant lid (which is the lithosphere in purely thermal models). The attractiveness of this approximation is that it allows to use a very simple approach to estimate, to first order, the global average lithospheric thickness and its variations, despite the complexities and the uncertainties of the dynamics beneath the Venusian lithosphere. The application of the ISL approximation to Venus gives a relatively thick lithosphere, about 600 km, which is on the high end of previously proposed estimates. A corollary of these findings is that the convection may manifest itself primarily through the thermal thinning of the lithosphere and that deep mantle dynamics may not be as easily recoverable from gravity and topography anomalies as previously thought.

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