GEOID TO TOPOGRAPHY RATIOS ON VENUS AND IMPLICATIONS FOR CRUSTAL THICKNESS.
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Introduction: The crustal thickness of a terrestrial planet provides an indication of the extent of mantle melting and as such is an important parameter in petrological and geodynamical modeling. To date, a number of complications have prevented the construction of a comprehensive crustal thickness map for Venus. In contrast to the Moon, Venus lacks seismic data with which to constrain the depth of the Moho. Even if a value for the average crustal thickness is chosen, the calculation of a global crustal thickness map of Venus from gravity data presents a challenge due to the fact that support of Venus' topography likely comes from a number of sources, including: (1) isostatic compensation from crustal thickness variations, (2) lithospheric stresses, (3) density anomalies within the crust or mantle, and (4) dynamic support.

Lithospheric stresses are only relevant on small scales, and we can use geoid to topography ratios to identify regions experiencing dynamic support (from plumes or mantle drips). Therefore, this study emphasizes long-wavelength gravity and topography features to distinguish between the effects of crustal compensation and dynamic support.

Data: NASA's Magellan mission to Venus, which ended in 1994, provides the best available gravity and topography data. Spherical harmonic coefficients have been produced for topography up to degree and order 360 [1], and gravity coefficients have been estimated to degree and order 180 [2]. The power spectrum for gravity noise surpasses the power of the estimated coefficients above degree 70 (spatial block size ~ 270 km), so we truncated both data sets at this point.

Geoid to Topography Ratios: We can estimate the GTR at a point on the planet by finding the least squares slope of the geoid over the nearby topography. We evaluated topography and the heights of the geoid at ~3000 points and then calculated GTRs on a rectangular grid (Fig. 1). The least squares calculation at each grid point incorporated all gravity and topography data within a 1000 km radius.

GTRs themselves are subject to variable uncertainty over the surface of the planet. The linear least squares problem tends to be well-conditioned over regions with large topographic variation and is comparatively ill-conditioned over smooth terrain (see Fig. 2). Many of the most extreme GTR values correspond to a high condition number, and may not be indicating any real physical phenomena. In the relevant regions, our estimates of GTRs match the estimates of a pre-Magellan study [3].

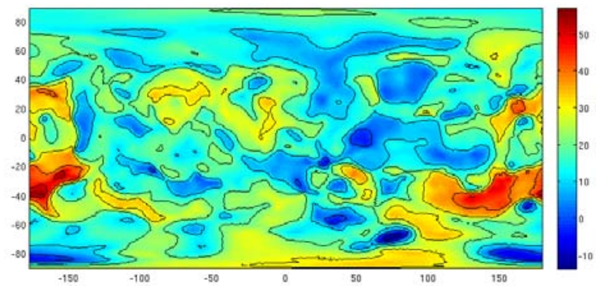

Fig. 1 – Geoid to topography ratios in m/km

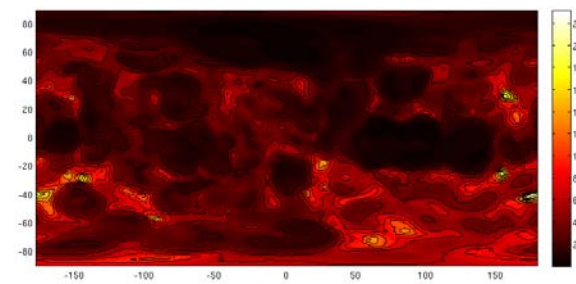

Fig. 2 – Condition numbers for the least squares problem

High GTRs serve as a proxy for dynamic support of the crust in a given region, so an analysis of crustal thicknesses is made by excluding regions with high GTRs. A histogram of the GTR distribution on Venus is slightly double-peaked around 16 m/km, so in this study we consider crustal thickness constraints in regions with GTR<16 m/km.

Crustal Thickness Map: Crustal thicknesses can be calculated by downward continuing Bouguer gravity anomalies to an interface below the surface. We assume that all gravity anomalies result from a combination of surface topography and variations of the crust-mantle interface. Since surface topography is known to a high degree of accuracy, we can downward continue the Bouguer potential anomaly to an interface at a predetermined depth below the surface, the mean crustal thickness, and invert for relief on the Moho.

The gravitational potential produced by relief on the surface and at the Moho can be approximated to first order using 2-D surface densities. However, this approximation is not appropriate for large variations in Moho topography. In order to account for finite amplitude topography, we use an algorithm that expands powers of topography into spherical harmonics [4]. This method was derived to solve for the highly variable crustal thicknesses on the Moon, and was later used to solve for the similarly dramatic crustal thicknesses on Mars [5]. Venus does not display any deep impact basins (the lowest point on the planet is about 2 km below the reference ellipsoid), so the finite amplitude corrections have only a minor effect on our crustal thickness calculations.

In order to downward continue Bouguer anomalies to the Moho, we are required to estimate the mean crustal thickness *a priori*. An obvious lower bound on mean thickness is the requirement that crustal thickness must be greater than zero everywhere. However this does little to constrain the crustal thicknesses on Venus due to its lack of deep basins. A second consideration for choosing a mean crustal thickness is the basalt-eclogite phase transition [6, 7]. With increased pressure, basalt in the crust will convert to garnet granulite and eclogite, increasing its density. Even if the eclogite does not delaminate from the base of the crust it will effectively cancel out the crust/mantle density contrast. Additionally, density will increase with depth as the crustal thickness proceeds into, and through, the garnet granulite stability field. Phase transition depths are dependent on the geotherm, but if the crustal thickness is constrained by the phase transition and by the solidus, no crust thicker than about 70 km should be reasonably expected. (see Fig. 3).

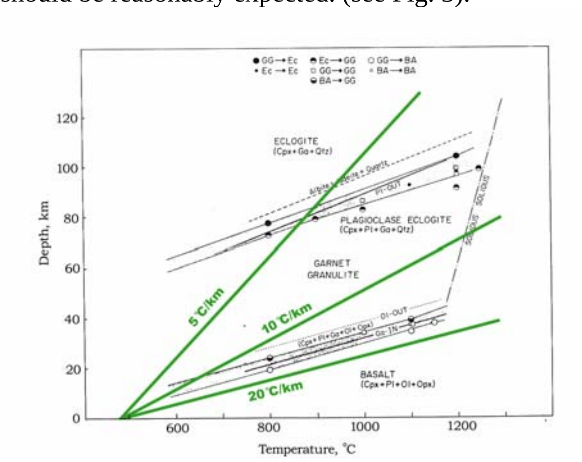

Fig. 3 – Linear geotherms plotted over the mantle phase transitions (modified from [7]).

For the entire range of mean crustal thicknesses being considered, nearly all regions of high topography are isostatically undercompensated and most basins are overcompensated. Since this isostatic residual is reduced at larger crustal thicknesses, we choose the largest mean thickness that does not result in crust anywhere extending below the basalt-eclogite phase transition. With this constraint, we find that the mean crustal thickness is roughly 30 km (see Fig. 4). This may plausibly be considered an upper limit.

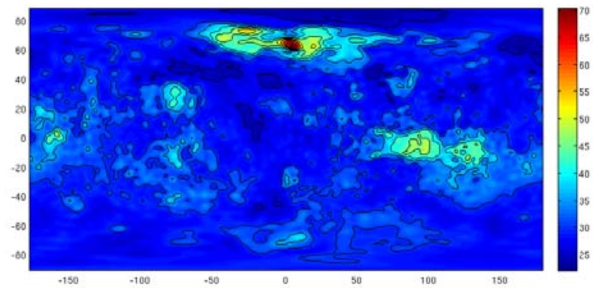

Fig. 4 – Crustal thicknesses with a contour interval of 5 km, based on a mean crustal thickness of 30 km.

Conclusions: We have produced a global map of crustal thickness and have calculated geoid to topography ratios over the surface of Venus. Our calculated mean crustal thickness of 30 km implies that crustal material constitutes 1.5% of the planetary volume.

Notable in the data is the lack of any large mass concentrations, or "mascons". Mascons are broadly defined to be regions of positive density anomaly in the crust and are usually associated with ancient impact events. Unlike the gravity observed on the Moon and Mars, the gravity on Venus has no large anomalies uncorrelated with topography. There are several possible explanations for the apparent absence of mascons. Firstly, viscous relaxation to a state of isostasy in the crust could conceivably cause topography above the mascon to subside without leaving behind flexural signatures. This is consistent with traditional ideas of a weak lithosphere on Venus, although the current consensus is that the surface is capable of supporting flexure on long timescales [8, 9]. Secondly, a mascon can be hidden by a very thick crust relative to the wavelength of the anomaly. Finally, we will note that a lack of mascons in the crust is consistent with a catastrophic overturning of the Venusian surface at 500 Ma or earlier, during which any buried heterogeneities could have been recycled into the mantle.

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