

# Formation of Ishtar Terra, Venus: Surface and gravity constraints

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## ABSTRACT

**We examine the geology of Ishtar Terra, Venus, as viewed in high-resolution Magellan synthetic-aperture radar imagery and altimetry, in order to interpret regional surface strain patterns. We combine constraints imposed by the surface strain with gravity modeling of Magellan degree-75 high-resolution gravity data. Long-wavelength (>2500 km) and short-wavelength (500–2500 km) features show different apparent depths of isostatic compensation. Ishtar straddles a long-wavelength topographic bulge that is compensated at  $\sim 130 \pm 40$  km depth, whereas the short-wavelength features (individual mountain belts and tesserae) are compensated at varying depths in a range of  $\sim 25$ – $70$  km. These two ranges of compensation, taken together with surface strain patterns, lead us to postulate a new model for the evolution of Ishtar Terra. In the model, mantle downflow results in ponding and thickening of partial melt residuum that compensates the long-wavelength bulge of Ishtar Terra. Thickened lower crust, resulting from shear forces associated with structurally deeper residuum, isostatically compensates short-wavelength topography. Relative displacement of the lower crust beneath the upper crust, which deforms in ruglike fashion, results in the surface strain patterns.**

## INTRODUCTION

The origin of Ishtar Terra, one of two prominent topographic uplands on Venus, is fundamental to understanding Venusian tectonism. Ishtar Terra comprises a high plateau, Lakshmi Planum (4 km above mean planetary radius [MPR]), rimmed by deformed belts (Fig. 1). Previous models for Ishtar formation include mantle upwelling, mantle downwelling, and horizontal convergence. These models, originally derived from Pioneer Venus and Venera data, are too simple to predict patterns in surface strain, topography, or gravity. Magellan synthetic-aperture radar (SAR) imagery, altimetry, and gravity (spherical harmonic degree-75 [half-wavelength resolution  $\sim 250$  km]) data allow us to examine Ishtar Terra at much higher resolution. We propose a model for the formation of Ishtar Terra in which mantle downflow results in variable thickening of mantle melt residuum and the lower crust; differential translation of the lower crust relative to the upper crust is responsible for surface strain.

## ISHITAR DEFORMED BELTS

Ishtar Terra includes Lakshmi Planum and the surrounding mountain belts Maxwell, Danu, Akna, and Freyja montes (3.5–11 km above MPR) and outboard tesserae western Fortuna, Clotho, Atropos, and Itzpapalotl (1–4.5 km above MPR), respectively (Fig. 1). Uorsar Rupes marks the steep slope along the northern boundary of

Itzpapalotl, and Vesta Rupes and Danu bound Lakshmi to the south. The North Basin (Kaula et al., 1992) is a topographic deep between Maxwell and Freyja. The high plain of Lakshmi is relatively structureless, except for contractional wrinkle ridges along its periphery.

Contractional fold ridges and valleys (Campbell et al., 1983; Solomon et al., 1991), which are continuous along strike for hundreds of kilometres, dominate the tectonic fabric of the montes and tesserae. In Maxwell–western Fortuna and in Akna–Atropos, parallelism of structures defines a coherent tectonic fabric that extends from Lakshmi wrinkle ridges across the mountain belts and into adjacent tesserae. Fold spacing (3–15 km range,  $\sim 6$  km average) does not change from mountain belt to tessera despite several kilometres elevation change (Keep and Hansen, 1994b); thus, topography, and not tectonic fabric, distinguishes mountain belts from tesserae. We interpret the similarity in fold spacing and orientation to record similar bulk strain across hundreds of kilometres normal to structural trend and across several kilometres change in elevation; i.e., no strong strain gradient is observed. Surface crustal contractional strain is low ( $<30\%$ ), assuming that the ridges are continuous parallel-style folds with amplitudes of 1–2 km (almost certainly a gross exaggeration). In plan view the mountain belts and tesserae each have length (parallel to structural trend) to width (normal to

structural trend) ratios of  $<4$ , with the exception of Danu Montes. In comparison, many Earth mountain belts have length/width ratios  $>10$ . Maxwell, Akna, and Freyja have steep slopes inward toward Lakshmi and gentler slopes outward toward their tesserae.

Danu Montes and outboard Clotho Tessera are different from their Ishtar counterparts. Danu is a long, narrow mountain belt 1.5 km above Lakshmi; Clotho is 1–1.5 km above the MPR and is dominated by linear troughs of extensional origin (Smrekar and Solomon, 1992). Fold ridges overprinted by parallel extensional grabens in Danu and Vesta Rupes are parallel to their respective boundaries with Lakshmi, implying that contraction normal to the southern Lakshmi boundary was followed by local late-stage collapse (Keep and Hansen, 1994a).

Maxwell rises steeply from Lakshmi and slopes gently east to Fortuna (Fig. 1). The fold belt trends north-northwest across the main body and ends abruptly along strike at the base of the north and south slopes; there is no evidence of a truncating structure (Keep and Hansen, 1994b). Despite the high elevation of Maxwell, the north and south slopes are the only regions that show evidence of crustal extension (Smrekar and Solomon, 1992; Kaula et al., 1992).

Western and eastern Freyja trend east and north, respectively; each has fold belts parallel to its respective trend. Polyphase in-

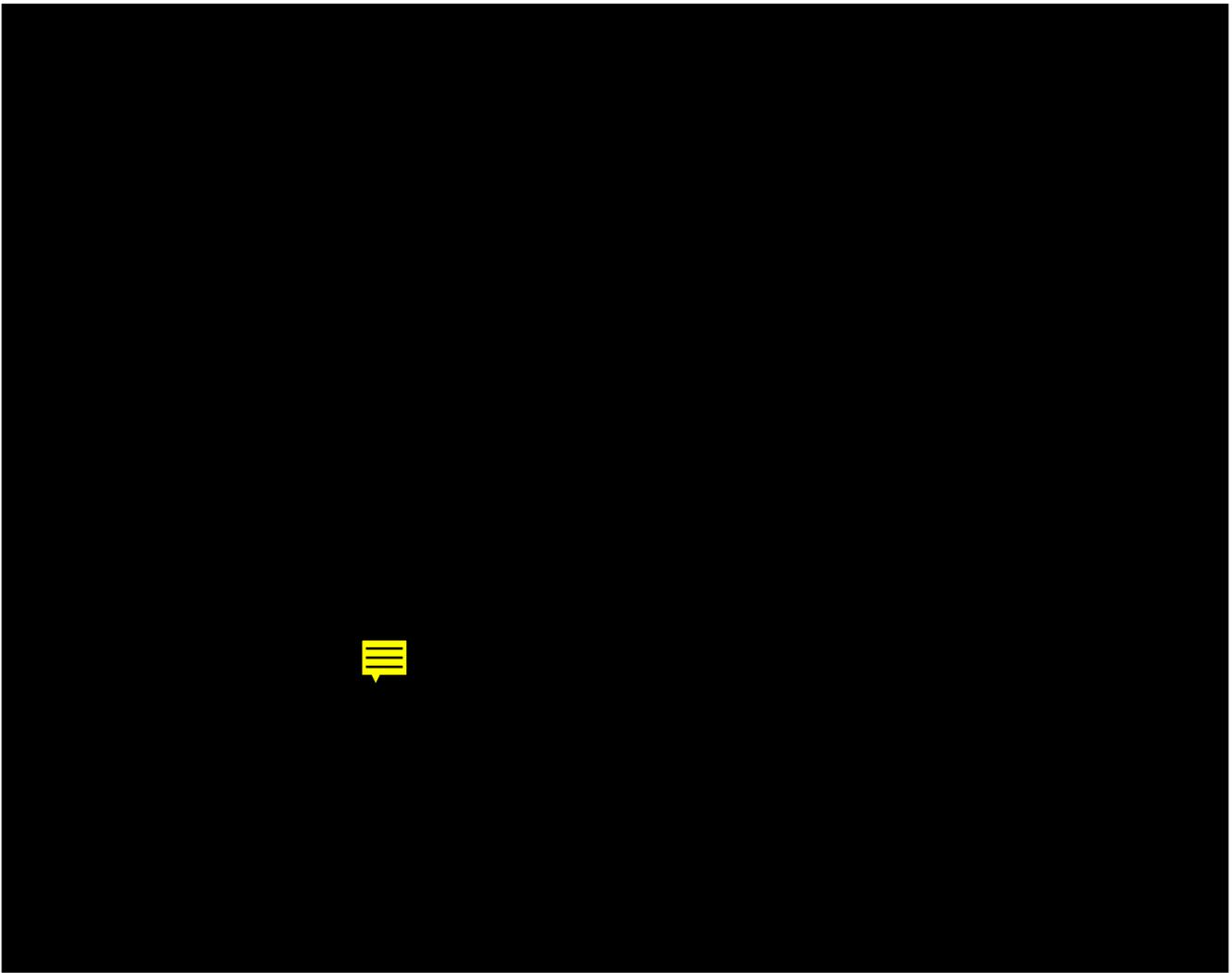


Figure 1. Synthetic-aperture radar image of Ishtar with long-wavelength topography (red) and topographic profile (trace in blue). Insets show feature locations and view of surface folds from Akna Montes. MPR is mean planetary radius.

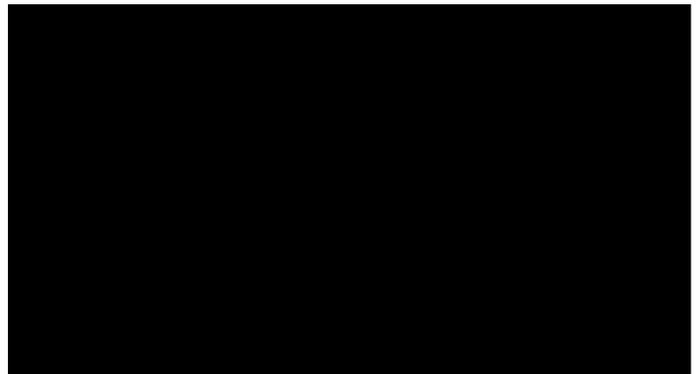
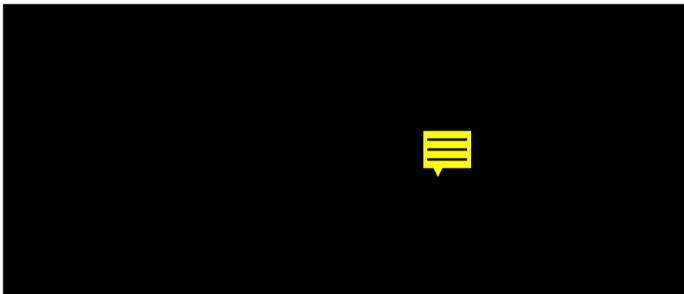
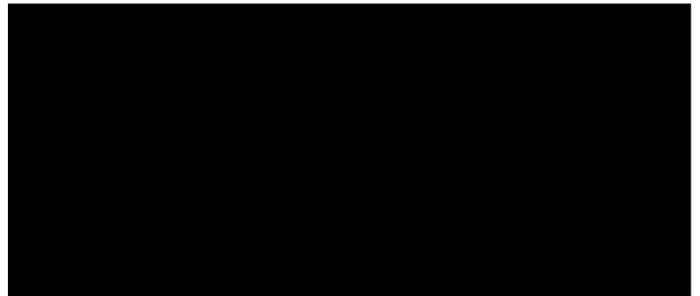
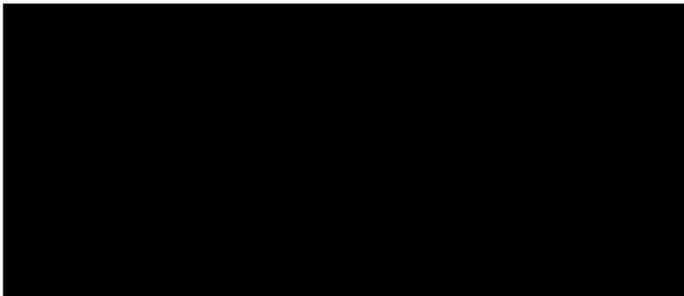


Figure 2. Sinusoidal projection of (A) spectrally separated topography with wavelengths  $\ell \leq 16$  shown as contours plotted on color image of  $\ell \geq 16$ , and contoured isostatic anomalies for depth  $D = 30$  km (B) and 50 km (C), for  $\ell \geq 16$ . Dashed lines are negative contours; contour interval is 1 km (A) or 20 mgal (B) and (C).

Figure 4. Cartoon of Ishtar model (not to scale).

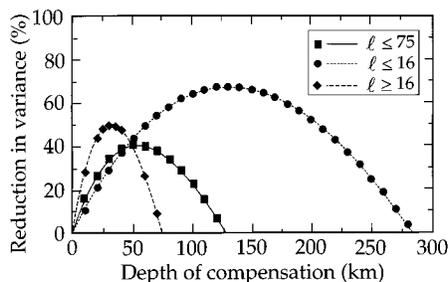
terference dome-and-basin structures mark the region of overlap (Kaula et al., 1992). Extensional grabens that parallel the boundary of the montes and Lakshmi overprint folds of both ranges indicate local gravitational collapse (Kaula et al., 1992; Smrekar and Solomon, 1992). North of Freyja, Itzpapalotl displays an asymmetric tectonic fabric that may record >250 km relative left-lateral displacement between Freyja Montes and the northern plains (Hansen, 1992).

### GRAVITY CONSTRAINTS

Gravity analysis was carried out by the *simple* calculation of isostatic anomalies for which spherical harmonic representations of gravity and topography based on Magellan mission data were used. The topography was obtained from a 360th degree and order (half-wavelength resolution ~50 km) model (Rappaport and Plaut, 1994). The gravity field information was obtained from a 75th degree and order model (W. L. Sjogren model; 1994, personal commun.) that incorporates Magellan high- and low-altitude quasi-circular orbit data gathered over Ishtar Terra. The model was not subject to any a priori constraints in the Ishtar region, so gravity anomaly amplitudes there can be considered to be reasonably reliable (see Konopoliv and Sjogren, 1994). The spectrum was divided into long- and short-wavelength portions at degree  $\ell = 16$ . This corresponds to a wavelength of ~2500 km and was selected so that for  $\ell \leq 16$ , the wavelengths exceed the basic linear dimension of Lakshmi Planum and its surrounding mountain belts.

The long-wavelength topography of Ishtar (Fig. 2) forms a broad dome or welt trending northwest about 5000 km and corresponds approximately to the limits of Ishtar deformation (tessera terrain) (Fig. 1). Lakshmi Planum is not distinctive topographically; it occupies merely the highest part of the welt. The mountain belts and the North Basin and high parts of Fortuna Tessera are superimposed on the dome.

The isostatic anomaly,  $g_{\text{iso}}(x, y)$ , is defined as the residual remaining when the gravity effect of topography plus a compensating mass at depth  $D$  is subtracted from free-air gravity,  $g_o(x, y)$ . For a particular feature, the isostatic anomaly as a function of  $D$  changes sign at the correct compensation depth (positive to negative with increasing  $D$  for positive elevation and the opposite for negative elevation). We have used a single reference depth for the compensation; in actuality compensating mass anomalies are density variations from this surface. In the case of mountain roots, the compensation depth is underestimated, perhaps by 20%–30%. The



**Figure 3.** Plot of depth of compensation vs. reduction in variance for isostatic model fits to observed gravity in Ishtar region;  $\ell$  is wavelength.

reduction in variance,  $\chi$ , of the free-air gravity field by the isostatic model gravity field as a function of  $D$  is given by

$$\chi(D) = \left\{ 1 - \left[ \frac{\sum_{x,y} g_{\text{iso}}(x,y)}{\sum_{x,y} g_o(D,x,y)} \right] \right\} \cdot 100,$$

and is shown in Figure 3 for three different spectral bands ( $\ell \leq 75$ ,  $\ell \leq 16$ ,  $\ell \geq 16$ ). Splitting the spectrum at  $\ell = 16$  increases the reduction in variance and suggests that there are two distinct modes of compensation, although the broad peaks in the functions suggest that the compensation mechanism is spread over a depth interval. For  $\ell \geq 16$ , lateral variation in  $D$  may be the major cause of peak broadness (Table 1). B and C of Figure 2 show contours for the isostatic anomalies for  $D = 30$  km and 50 km, respectively, for  $\ell \geq 16$ . At  $D = 30$  km, Maxwell, Akna, and North Basin have positive anomalies, whereas the anomaly over Freyja is close to zero. At  $D = 50$  km, the anomalies over Maxwell and Freyja are distinctly negative, indicating that the compensation depths for these two features must lie between 30 and 50 km. Given the depths of compensation found here for the short-wavelength features, the most likely mechanism of compensation is variation in crustal thickness (i.e., Airy compensation at the Moho). The broad peak in  $\chi$  for  $\ell \leq 16$  indicates a compensation range  $\sim 130 \pm 40$  km for long wavelengths, consistent with the results of Grimm and Phillips (1991).

### KEY OBSERVATIONS

Key observations that models for Ishtar Terra must satisfy include (A) Ishtar's, topographic profile, including high interior plateau, peripheral mountain belts, and surrounding high tesserae, which result in a broad topographic dome or welt upon which are superimposed the mountain ranges, with steep slopes oriented inward toward Lakshmi and gentle slopes transitional to

**TABLE 1.** COMPENSATION DEPTH RANGE FOR FEATURES IN THE VICINITY OF ISHTAR

TERRA, $\ell > 16$	
Location	Compensation depth (km)
Maxwell Montes	35--45
Freyja Montes	30--40
Akna Montes	60--70
North Basin	15--25
Metis Regio	25--45
N. Fortuna Tessera	35--45
W. Fortuna Tessera	25--35

tesserae; (B) structural fabrics, dominated by fold ridges, parallel to the orientation of their respective host mountain belt with Lakshmi, which itself is generally undeformed at the surface; (C) coherent fold patterns across hundreds of kilometres normal to strike that record no obvious strain gradient despite several kilometres change in elevation, although fold belts end abruptly along strike; (D) lack of evidence for extensional collapse at the highest elevations; (E) mean crater retention age of several hundred million years (Phillips et al., 1992); and (F) new gravity constraints: degree-75 Magellan gravity illustrates that short- and long-wavelength features are compensated at different depths; short-wavelength (500–2500 km) features have variable depths of compensation, ranging from 25 to 75 km, whereas long-wavelength (>2500 km) features are compensated at ~130 km.

### PREVIOUS MODELS

Pre-Magellan convergent plate-tectonic models (e.g., Crumpler et al., 1986; Head, 1990; Roberts and Head, 1990) call for subduction all around Lakshmi, or at least along Uorsar Rupes and Vesta Rupes. We reject these models on plate-scale kinematic and structural grounds. Southward subduction along Uorsar Rupes requires that Akna and Maxwell are left-lateral and right-lateral shear zones, respectively, whereas northward subduction along Vesta Rupes would require the opposite shear sense in each belt. Subduction along the eastern, northern, and western margins (to accommodate observed contractional structures) is kinematically difficult; subduction would require radial contraction in the subducting lower plate, or radial extension in the upper plate, or both; neither is observed.

Ishtar crustal shortening and long-wavelength topography have been variably interpreted as the result of mantle downwelling (e.g., Bindschadler and Parmentier, 1990; Lenardic et al., 1991; Bindschadler et al., 1990, 1992) and mantle upwelling (e.g., Pronin, 1986; Basilevsky, 1986; Grimm and Phillips, 1991). Both of these models are based on long-wavelength Pioneer Venus

gravity data, and each assumes a single compensation mechanism for Ishtar; they do not address relations derived from short-wavelength topography or surface strain.

The mantle downwelling (or coldspot) model asserts that thickened crust supports the long-wavelength welt of Ishtar Terra as well as a sinking mantle diapir, which pulls crustal material inward and downward beneath Lakshmi. Initially the surface is deflected downward until the crust thickens, resulting in high surface elevation. When downwelling ceases, the thickened crust spreads gravitationally decreasing in elevation. Several arguments against this model can be made. (1) The time scales required for the proposed large-scale crustal flow are not geologically reasonable (Phillips and Hansen, 1994) and may approach 1 b.y. (2) The model calls on huge volumes of lower crust to thicken Ishtar Terra, yet it does not identify evidence of structures that produce or transport large volumes of lower crust. (3) Dynamic support of high-standing topography driven by inward flow of the lower crust places the surface and upper crust in tension (Kiefer and Hager, 1991); therefore, this model predicts surface extension, rather than contraction. In addition, if the downwelling model is correct, then the crust must participate in compensation of both the long- and short-wavelength topography. The compensation depth from the downwelling model does not represent a physical surface but is a mathematical construct providing a balance between the gravity contributions of overthickened crust ( $-\Delta\rho$ ) and a sinking mantle diapir ( $+\Delta\rho$ ). Grimm and Phillips (1991) presented solutions that reproduced the correct compensation depth (130 km in their analyses) and maximum elevation (4 km) at western Ishtar Terra with Moho depths of 42 to 58 km (background crustal thickness of 20 km) and mantle sinker depths of 230 to 270 km. This Moho depth range falls within the range found here (Table 1). However, the various compensation depths for short-wavelength features should sample a long-wavelength part of the Moho surface that is correlated with long-wavelength surface elevation if the downwelling model is correct. This is certainly not the case (compare Table 1 to Fig. 2A).

In the upwelling (or hotspot) model (Grimm and Phillips, 1991), Ishtar Terra comprises the surface expression of a hotspot that produces topography dynamically and by volcanic construction, and the deformed belts result from incipient mantle return flow that has encountered a lateral strength heterogeneity—the central region over the upwelling has been weakened by excess heat flow and magmatic activity (Pro-nin, 1986; Basilevsky, 1986). For both the

upwelling and downwelling models, it is possible that mountain belt topography can be formed by contraction across a lateral strength heterogeneity and could be supported in part by lithospheric strength (Zuber and Parmentier, 1993). The gravity analyses presented here do not rule out this model, because two distinct mechanisms (crustal thickening beneath mountain belts and deep dynamic support of long-wavelength topography) would explain the short- and long-wavelength gravity results. However, this model does not explain the mountain belt-scale topography nor observations A–D above. Upwelling predicts radial extension; no evidence for this is observed. Although deceleration of outward plume flow at the plateau margin might result in accumulation of the crust to form mountain belts, the hotspot model would predict steep slopes outward from the mountain belts, contrary to the observed steep inner slopes (Fig. 1), and the hotspot model does not account for the parallelism of the tectonic fabrics in the mountain belts and tesserae.

## DISCUSSION

Our analysis of degree-75 Magellan gravity illustrates that short- and long-wavelength features are compensated by different mechanisms; thus, successful models for Ishtar Terra must provide an element of buoyant support of the long-wavelength topographic welt, but this support cannot come from the crust-mantle boundary (as in the coldspot model). A hotspot model might be invoked, but it flies in the face of tectonic constraints, as discussed above. What is required is a subsurface mechanism that is buoyant (negative density contrast with surroundings) but at the same time is able to apply significant inward-directed shear traction to the overlying lithosphere to thicken the crust locally.

Our model begins with observations A–D, addresses the wavelength-dependent compensation constraints, and is developed within the context of the theoretical and geophysical constraints outlined by Phillips and Hansen (1994, see references therein), the most pertinent of which are the following. (1) The lower crust of Venus is weaker than the mantle beneath and the overlying upper crust and is able to flow on geologically reasonable time scales. This result is consistent with recent estimates of elastic lithosphere thickness, which can exceed 40 km (Phillips, 1994). For even modest crustal thicknesses ( $\sim 20$ – $30$  km) and temperature gradients ( $10$ – $15$  K km $^{-1}$ ), the short-wavelength structures in the Ishtar region require lower crustal flow (Zuber, 1987), even in light of new laboratory measurements suggesting that Venus has a very strong crust

(Mackwell et al., 1994). (2) The upper mantle beneath Ishtar comprises mantle residuum that, because of its higher magnesium content relative to normal mantle, is compositionally more buoyant than undepleted mantle and mechanically stronger (due to a higher solidus temperature). (3) The lower crust can detach from the upper crust along a ductile decollement. (4) Viscous mantle flow can induce horizontal stresses in the lithosphere and cause intense tectonic deformation. (5) The lithosphere is limited in its ability to move horizontally due to lack of a low-viscosity zone beneath it.

Observations A–D require a mechanism to deform huge expanses of crust without developing strong strain gradients, regardless of changes in topography. If deformation resulted from stress transmitted horizontally through the crust across a (sub)vertical mechanical boundary, strong strain gradients might be expected, the highest strain being closest to the mechanical discontinuity. No obvious strain gradient is observed; strain probably resulted from shear stresses transmitted upward across the expanse of deformed crusts. Basilevsky et al. (1986) and Phillips (1986) suggested that large regions of deformation on the surface of Venus might result from sublithospheric flow.

We propose that the long-wavelength topography is isostatically compensated by thickened residuum and that the mountain-belt-scale, short-wavelength topography is compensated by variably thickened lower crust (Fig. 4). The residuum is a natural by-product of partial melting of the mantle. On Earth, the residuum from partial melting in the oceanic upper mantle is probably swept into the continents by plate motion (Kaula, 1990), forming the mantle keel, or tectosphere, that extends beneath the continents (Jordan, 1975, 1981). Venus lacks large-scale plate motions (Solomon et al., 1992), so residuum should be more widely distributed, but subject to disruption due to, in the absence of subduction, remixing associated with instabilities “dripping” from the cold upper thermal boundary layer of mantle convection. It is probable that only the lower part of the residuum, being less viscous and negatively buoyant, is able to participate in the thermal boundary-layer mechanics (Parmentier and Hess, 1992). The upper part of the residuum would pond and form a “keel,” perhaps similar to the tectosphere except that it is buoyant. This is the model we envisage for Ishtar Terra. Although the crust is thicker beneath Akna Montes than beneath Maxwell Montes, Maxwell is topographically higher than Akna because it lies above a thicker part of the residuum pond (Figs. 1, 2, and 4). Lakshmi Planum, which

lacks evidence of surface deformation, is topographically high because it is near the axis of the residuum keel, not because it is underlain by thickened crust.

The upper part of the residuum flows, but more likely imbricates quasi-brittlely in response to shear forces associated with the instability flow developed in the lower part of the residuum layer. The shear forces are transmitted to the crust and are at a maximum in those regions where the velocity gradients in the residuum are greatest; i.e., at intermediate distances from the geographical center of the residuum, where inward-directed flow turns downward. These regions would mark the locations of maximum shear thickening of the crust—due to horizontal flow and imbrication in the weak lower crust—and formation of mountain belts. Relative westward, southward, and eastward translations and imbrication and/or flow of lower crust toward Lakshmi are responsible for Maxwell, Freyja, and Akna montes and their outboard tesseræ, respectively. The narrow character of Danu Montes implies little relative northward displacement of the lower crust, as might be expected given the location of this belt relative to the shape of the residuum at depth as reflected by the long-wavelength topography (Figs. 1 and 2A).

Ishtar surface strain results from differential translation of the lower crust beneath the upper crust. The upper crust is partially decoupled from the lower crust such that shear stresses are transmitted from the lower crust to the upper crust, across a structure analogous to a “roof thrust,” causing the upper crust to crumple and fold like a rug, with fold axes perpendicular to the direction of lower crust translation. Displacement of the lower crust relative to the upper crust is responsible for the surface patterns, and the imbrication or flow of the lower crust is responsible for the short-wavelength topography (Fig. 4). This is not a uniform process, as indicated by the varying compensation depths of short-wavelength topography (Table 1). Translation of the lower crust inward toward Lakshmi, in response to upper residuum shear traction, could result in a broadly synchronously strained surface over thousands of kilometres marked by parallelism of fold axes. The surface would be deformed wherever the lower crust is displaced at depth relative to the upper crust. Gravitational instabilities might occur along steep slopes or in regions of enhanced crustal thickening due to polyphase deformation.

Detailed geological mapping and quantitative thermomechanical modeling will provide further tests of the hypothesis presented here.

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