Isostatic Compensation of Ishtar Terra, Venus

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Abstract

We have used spherical harmonic representations of the Venus topography and geopotential, obtained from Magellan data, to evaluate isostatic support in several areas within the Ishtar Terra highlands including the Lakshmi plateau, its surrounding mountain belts namely Akna and Freyja, and Maxwell Montes, and the Fortuna Tessera province. We find that topography in Ishtar is largely compensated (>80%). Regional geoid-topography variations in the subregions can be explained by a combination of Airy (crustal thickening) and thermal (lithospheric thinning) mechanisms. This implies that Venus has a thick reference thermal lithosphere (~ 300 - 400 km). With the exception of eastern Fortuna, lower elevation areas (h < 3-4 km) with large geoid-topography ratios (GTR) seem to be associated, to various degrees, with thermal isostasy, whereas the higher areas (h > 4 km) with lower GTRs are almost certainly Airy compensated via thickened crust. Relatively large (>60 km) total Airy crustal thicknesses obtained in the western Ishtar mountain belts, together with a probable basalt-eclogite phase change, suggest a silicic composition for these structures provided they are older than -25-50 Ma. Lakshmi Planum seems essentially thermally supported, with the thermal lithosphere thinned to ~ 100 km. We suggest, as one possibility, that the lithospheric thinning process under Lakshmi is delamination of a dense eclogite lower lithosphere layer into the mantle. The decrease in GTR observed in Ishtar from west to east (GTR ~ 20 m/km in Lakshmi, ~ 8 m/km in

Maxwell and west Fortuna, and ~ 4 m/km in eastern Fortuna) may correspond to a decay in thermal compensation attributed to lithospheric delamination, which would be fairly recent in Lakshmi, partially decayed in west Fortuna, and absent in east Fortuna where a mostly Airy-supported topography is essentially relaxed with no thermal uplift. Alternatively, if surficial concentrations in radiogenic elements were prevalent throughout the crust, partial melting of a thickened crust could account for the thermal uplift in Lakshmi and west Fortuna. The zero-elevation basaltic crustal thickness H ~ 24 km obtained for the east Fortuna Tessera region may be representative of the ambient crustal thickness in the Venus lowlands. Our findings support multi-component models for tectonic and volcanic activity in Ishtar, possibly including crustal convergence and underthrusting in the mountain belt areas, driven by full and/or partial subduction. The thick ambient crust and thermal lithosphere implied by this study agrees with observational constraints such as support of extreme elevations, large topographic slopes, unrelaxed craters, and the thick elastic lithosphere suggested by flexure studies. If the ambient thermal lithosphere on Venus were to be relatively thin(~ 100-200 km), with a cold mantle and radiogenic elements concentrated in the crust, then thermal evolution on Venus may be in quasi-steady-state, with the geodynarnic evolution in monotonic decline. However, if the ambient thermal lithosphere is very thick (-300-400 km), as suggested by our thermal model fits, then it is consistent with the predictions of strongly unsteady-state thermal evolution models and an interior which is currently heating up. This would support the view that catastrophic resurfacing on Venus might be episodic.

Introduction

Ishtar Terra is a highland province which includes the highest topography on Venus and extends in the northern hemisphere from ~ S5° < latitude <80°, and ~ -50°<longitude <60° E. With a horizontal extent of more than 4000 km, it spans an area about the size of Australia [*Janle and Jannsen*, *1984]* and has many tectonic features which exhibit compressional characteristics *[Roberts and Head,* 1990a; *Kiefer and Hager,* 1991]. In the western part of Ishtar is Lakshmi Planum, a plateau area which slopes upward from south to north with elevations ~ 3 - 4 km above the mean planetary radius (MPR) [*Ford and Pettengill*, 1992]. **This** high plains region is radar smooth and dark, and is apparently covered for the most part by volcanic deposits [*Kaula et al.*, *1992];* these lava flows appear younger than the ridged older terrain (tessera craton) that they seem to embay [*Smrekar and Solomon, 1992; Roberts and Head, 1990a,* b]. Within Lakshmi are two deep volcanic caldera, Colette Patera and Sacajawea Patera, whose floors lie 3 and 2.5 km below the surface [*Ford and Pettengill*, 1992]. Surrounding the Lakshmi plateau are linear mountain belts consisting of parallel banded structures *[Campbell et al., 1983]* and ridges and troughs *[Pronin, 1986; Pronin et al., 1986; Head,* 1990] which have long been interpreted as compressional with horizontal shortening [*Masursky et al.*, 1980; *Barsukov et al.*, 1986; *Kaula et al., 1992; Solomon et al.,* 1992]. These features appear to have many of the characteristics of terrestrial erogenic belts, namely anticlines, synclines, thrust faults, and strike-slip faults [*Crumpler et al.,* 1986; *Head,* 1990]. These belts include Akna and Freyja Montes (both ~ 6 km above MPR) on the northwest and north margins of Lakshmi, Danu Montes (~ 5 km above MPR) to the south, and Maxwell Montes to the east with the highest point on Venus (-10 km above MPR) [*Pettengill et al.*, 199 1; *Kiefer and Hager,* 1991; *Smrekar and Solomon,* 1992]. In the easternmost part of Ishtar lies a zone of highly deformed terrain, Fortuna Tessera, characterized by a pattern of intersecting ridges [*Barsukov et al.,* 1986; *Vorder Bruegge and Head, 1989],* which gradually slopes down from Maxwell to the east to ~ 2 km above MPR.

Providing constraints on compensation mechanisms in Ishtar should give insights into its tectonic origin and evolution. In turn, since Ishtar is one of the two highland structures of "continental" size on Venus (the other being Aphrodite Terra), this should lead to a better understanding of the thermal evolution of the planet. To study regional compensation mechanisms it is useful to perform correlations of topography variations with gravity or geoid (equipotential surface) anomalies for the area under consideration [*Haxby and Turcotte*, 1978; *Turcotte and Kucinskas*, 1993; *Kucinskas and Turcotte*, 1994].

Using Pioneer Venus Orbiter (PVO) altimetry and line-of-sight (1os) gravity data, *Sjogren et al.* [1984], and *Grimm and Phillips [1991]* found apparent depths of compensation (ADCs) for long wavelength (~ 2000 km) topographic features in western Ishtar Terra to be ~ 150 ± 30 km and ~ 180 ± 20 km, respectively. In view of these large ADCS, several authors suggested that topography in western Ishtar must be maintained by dynamic density anomalies due to mantle convective upwelling [*Basilevski*, *1986; Pronin*, *1986; Grimm and Phillips*, 1990, **1991],** or mantle downwelling [*Bindschadler and Parmentier*, *1990; Bindschadler et al.*, 1990; *Kiefer and Hager*, *1989, 1991].*

Indeed, there are basically two alternative mechanisms for the origin of topography and associated gravity anomalies, static and dynamic. On the Earth virtually all topography is attributed to static origins, either variations in the thickness of the crust or the lithosphere. This topography is compensated at wavelengths greater than about 200 km and this compensation within the crust or lithosphere is relatively shallow (< 100 km) so the associated gravity anomalies are weak. If Venus has an Earth-like mantle temperature and a steady-state thermal balance, between heat generation from radioactive isotopes and secular cooling and the surface heat loss, then the higher surface temperature on Venus will lead to a considerably thinner lithosphere on Venus than on the Earth. However, while the surface roughness on Venus is less than on the Earth, the highest topography is just as high. More significantly, the gravity anomalies associated with topography on Venus are considerably higher than on the Earth. This implies a greater depth of isostatic compensation inconsistent with a thinner lithosphere. This led to the hypothesis that topography on Venus is dynamically supported by mantle convection [*Kiefer and Hager,* 1989, 1991], with a thin (i.e. weak), hot global lithosphere in steady-state.

However, due to the high altitude of the spacecraft, PVO gravity data was of low resolution at the high latitudes of Ishtar Terra. The quasi-circularization of the Magellan spacecraft led to the acquisition of higher resolution gravity data over Ishtar [*Konopliv et al.*, 1994]. Several observations made with the Magellan data seem to preclude dynamic compensation models, particularly in Ishtar Terra. Indeed, whereas one would expect dynamic topography to be smooth and broad, Magellan altimetry revealed that the plateau margins and mountain belts in Ishtar Terra (especially the southwestern face of Maxwell Montes) exhibit abrupt changes in elevation over short horizontal distances (as little as 10 km or one altimeter footprint), resulting in slopes of more than 30° [*Ford and Pettengill*, 1992; *Smrekar and Solomon,* 1992]. Such sharp escarpments are difficult to explain via dynamic support as they would not reflect scales of mantle processes [*Smrekar and Solomon, 1992; Jull and Arkani-Hamed*, *1995]*. In fact, this topography is more likely to be supported by lithospheric stresses [*Turcotte*, *1993]*. Furthermore, a number of recent short and long wavelength studies using Magellan data sets suggest a thick ambient (or background) crust and lithosphere on Venus [*Sandwell and Schubert,* 1992; *Kucinskas and Turcotte*, 1994; *Phillips, 1994]*. Finally, *Turcotte* [1993] noted that it is difficult to reconcile a thick lithosphere and steady-state heat loss for an Earth-like mantle temperature, so that the thermal evolution on Venus might be strongly time dependent, as is also suggested by the cratering record on the planet [*Schaber et al., 1992]*.

In this paper, we have applied the isostatic approach given by *Kucinskas and Turcotte [1993;* 1994] for the Venus equatorial highlands to study the support mechanism in various subregions within the Ishtar Terra highlands. Our results are compared with the predictions of basic tectonic models for Ishtar and of catastrophic models describing the global geodynamic evolution of Venus.

Ishtar Data

We use the *75 x 75* degree and order spherical harmonic model for the Venus geopotential (MGNP75ISAAP) obtained from the high resolution cycle 5 and cycle 6 (circularized orbit) Magellan data [*Sjogren et al.*, 1995], along with the 360 x 360 harmonic model for the Venus topography [*Rappaport and Plaut*, 1994], truncated at degree and order 75, in order to obtain mean 2° x 2° local values of: (1) Bouguer gravity for an uncompensated topography (Δg^u); (2) observed gravity anomalies (Δg); (3) topography variations (h); and (4) geoid anomalies (N) for several sample areas located in the Ishtar highlands. Anomalies are determined with respect to a reference sphere of radius R_o = 6051.848 km (MPR of Venus).

The physiographic provinces we examined for isostatic compensation included:

- A large area covering most of Ishtar “1’errs, which we will call “Greater Ishtar” (GI).
- The broad, smooth high plateau of Lakshmi Planum, in western Ishtar, with elevations of ~ 3-4 km above MPR, labeled (L).
- An area including the narrow mountain belts of Akna and Freyja Montes, (A+F), rising -6 km above MPR; this sample also includes part of Atropos and Itzpapalotl Tessera to the north.
- A central Ishtar mountain belt province, namely the Maxwell Montes region (M), which includes the highest peak on Venus at ~ 10 km above MPR.
- A western Fortuna sample province (WF), namely an area of complex ridged terrain (tessera region), located between Maxwell Montes (-10OE) and ~ 30”E longitude, with average elevations of ~ 4 km above MPR.
- And last, the easternmost portion of Fortuna Tessera and Ishtar, (EF), spanning the range ~ 30”E < longitude < 60°E, mostly hilly terrain with lower elevations (~ 2 km above MPR).

The chosen areas are outlined by black rectangles in Figure 1a. Note that both the topography contour map (Figure 1a), and the geoid contour map (Figure 1 b) are for a rotated coordinate system with Maxwell Montes at 0° longitude, 0°

latitude. The Ishtar data values for h, N, Ag”, and Ag analyzed in this work were obtained in the rotated coordinate system.

Method of Analysis

Correlations of local gravity anomalies with topography give local degrees of compensation. If a region is fully compensated, the correlations between geoid and topography anomalies can be used to infer the mechanism of compensation and its depth. In a long-wavelength approximation the isostatic geoid anomaly is directly proportional to the dipole moment of the density-depth distribution [*Ockendon and Turcotte*, *1977; Haxby and Turcotte*, 1978]. Hence, once a density distribution is specified, one can use this relationship to obtain a theoretical expression for N in terms of h, which can then be compared to observed regional values of N to estimate model parameters [*Kucinskas and Turcotte*, *1994]*.

For each Ishtar region we performed a linear least-squares fit for the sampled data values of the Bouguer gravity anomaly BA = Ag” – Ag plotted versus Ag”. The regional degree of compensation C is defined as the slope of the best fit regression line for the Ag”, BA data set, We also perform, for each area considered, a least-squares fit of the observed geoid and elevation values to Pratt, Airy, and thermal isostasy correlations of N and h. For these three models, isostatic compensation and support of surface topography is achieved by horizontal variations in density, low density crustal roots, and thinning of the thermal lithosphere (thermal boundary layer) respectively. For the thermal thinning case, the lower part of the thermal lithosphere has been replaced by hot, lower density material resulting in a surface uplift h^{th} due to thermal expansion. The quadratic terms of the Airy and thermal isostasy models were predetermined by considering fixed values for the quadratic parameters.

For Pratt compensation, we have:

$$N_{Pratt} = \frac{\pi G}{g_o} \rho_o W h \tag{1}$$

with: $\rho_o = \rho_m = 3300$ kg m^{-3} (mantle density), $g_o = GM/Ro^2 = 8.87$ ms^{-2}, R_o = MPR = 6051.848 km, W the depth of compensation, and $h = R - R_o$ the elevation with respect to the MPR, with R the local planetary radius. For Airy compensation we have:

$$b(h) = \frac{\rho_c h}{(\rho_m - \rho_c)} \quad and \quad N_{Airy} = \frac{\pi G}{g_0} \rho_c \quad 2Hh + \frac{\rho_m}{(\rho_m - \rho_c)} h^2] \tag{2}$$

with: ρ_c = crustal density (here fixed to 2700 or 2900 kg m^{-3}); b is the thickness of the crustal root corresponding to elevation h, and H is the thickness of the crust with zero elevation (reference state). For thermal compensation elevation associated with the thinning of the lithosphere is:

$$h^{th} = 0.486\alpha(T_m - T_s)(y_{L_o} - y_L) \tag{3}$$

where y_{L_o} is the thickness of the lithosphere in the reference state of zero elevation, y_L is the thickness of the thinned lithosphere with thermal elevation h*, T_m is the Venus mantle temperature = 1500°K, T_s = Venus surface temperature = 750°K, and α= the volume coefficient of thermal expansion = 3 x 10^{-5}"K"^{1}. With respect to the reference state, the local geoid anomaly corresponding to a surface elevation of h fully compensated by thermal thinning of the underlying lithosphere is then:

$$N_{th} = \frac{\pi G \rho_m}{g_o}\left[1 + \frac{\pi}{2\alpha(T_m - T_s)}\right](2\omega_o h - h^2) \tag{4}$$

where $\omega_o = h^{th}_{max}$ is the maximum thermal elevation (uplift) attainable and corresponds to a totally thinned lithosphere (i.e. $y_L = 0$).

For a given region, we obtain the following model parameter values: for Pratt compensation the local geoid-to-topography ratio GTR = N_{pratt}/h and the corresponding value of W; for Airy compensation H and, for a given maximum regional elevation h_{max}, the total crustal thickness (not including h_{max}) T (h_{max}) = H + b (h_{max}); and, for thermal compensation, $\omega_o = h^{th}_{max}$ and the corresponding value of y_{L_o} and also, if applicable, the value of y_L (h_{max}) for a given maximum regional elevation h_{max}. We also evaluated the root mean squared error (rmse)σ

for each fit to the (h, N) data in a given region, as a measure of the goodness of fit.

Results and Discussion

Initially, we assume a basaltic crustal composition with density ρ_c = 2900 kg m“3 [*Surkov et al., 1984].* Results of the various model fits to the observed regional correlations for the six sample areas we considered are shown in Table 1. N/A (not applicable) in Table 1 corresponds to negative values of $y_L(h_{max})$. In Figure 2 we give 2° x 2° sampled data values of BA versus Ag” for each of our chosen regions, along with the best fit regression line. Figure 3 shows scatter plots of 2° x 2“ sampled N versus h data points for each region of interest, along with the best-fit curves for Pratt, Airy, and thermal compensation. For the entire Ishtar area, the correlation of the (Δg^u, BA) data shows strong coherence, and a high degree of compensation C > 80% for all samples. There is a significant decrease in regional Pratt and Airy parameter values (e.g. GTR, depth of compensation W, and Airy crustal thickness) in Ishtar from west to east. Parameter values are largest in Lakshmi Planum (GTR ~20 m/km) and lowest in east Fortuna (GTR ~4 m/km). These observations suggest the applicability of different mechanisms of compensation for different ph ysiographic provinces within Ishtar. This fact is most apparent in comparisons between the Lakshmi and Maxwell provinces. From the regional (h, N) correlation scatter plots, it appears we can distinguish between two trends in the data, Namely, one group of (h, N) points seems to have a low GTR, while another is associated with a high GTR. For higher elevations it is clear that points fall into the lower GTR category; this is especially apparent in the Greater Ishtar and Maxwell mountains regions. For lower elevations (h< 3-4 km), there is a mix of points from both these lower and higher GTR trends. The low elevations eastern Fortuna area seems the exception, with essentially low GTR, but there is more scatter in the data there than elsewhere in Ishtar. We believe this is evidence for a mix of modes of compensation.

Results of our model fits suggest the following compensation mechanisms: for the mountain belt provinces, namely Akna + Freyja (GTR -12 m/km), and Maxwell (GTR -8 m/km), we favor mainly Airy isostasy with H = 69 and 25 km, respectively, with a smaller thermal component (probably somewhat larger for the larger GTR, A + F area), for elevations h <3-4 km. Indeed, a purely thermal model fails to reproduce the observed data in these regions (i.e. $h^{th}_{max} \ll h_{max}$). For the Lakshmi plateau, (GTR -20 m/km), the large values of H and T (total crustal thickness) seem unrealistic, even with a thick global crust and lithosphere, while thermal compensation yields a good fit to the observable in this region. This suggests that a thick (~ 300 - 400 km) zero-elevation (i.e. ambient) thermal lithosphere, associated with a thick crust and elastic lithosphere, has thinned thermally to -100 km (for support of ~ 3 km mean elevations in Lakshmi). From the (h, N) plots we believe that a small Airy component is also present, at least for the support of the higher elevations. For west Fortuna (GTR -8 m/km), the plots and numerical results suggest that in this area thermal and Airy support mechanisms are almost equally represented. The east Fortuna area (GTR ~ 4 m/km), however, seems to be mainly Airy-compensated, though the (h, N) data in this region is less well correlated.

We now address some implications of the preceding results. Experimental work by *Green [1967], Green and Ring wood [1972.],* and *Ahrens and Schubert [1975]* showed that at pressures> 1.5- 3.0 GPa basalt is unstable and transforms to denser eclogite (ρ -3400- 3500 kgm^{-3}) via a garnet granulite assemblage. Based on these results, *Anderson [1981]* and *Turcotte [1989a]* argued that the thickness of the Venusian crust is likely to be limited. A basaltic crust on Venus would be expected to transform to eclogite at depths of 50 - 70 km [Hess *and Head, 1990; Arkani-Hamed*, 1993]; when the dense eclogite layer becomes sufficiently thick, lithospheric delamination into the mantle could then occur [*Turcotte*, *1989]*. Furthermore, several authors [*Vorder Bruegge and Head,* 1991; *Arkani-Hamed*, 1993; *Namiki and Solomon,* 1993; *Jull and Arkani-Hamed, 1995],* have pointed out that the gabbro-garnet granulite-eclogite phase changes would act as a limiting factor for the highest elevations (> 4-5 km) observed in Ishtar by reducing buoyancy of the crustal column, provided these structures are older than -25-50 Ma.

From the preceding discussion t seems reasonable to propose that either the highest mountain areas are quite young (< 25-50 Ma) and strong tectonic activity is contemporary on Venus (at least in Ishtar), or the mountain belts are composed primarily of non-basaltic material. In this context, while our earlier Airy modeling results for eastern Fortuna (EF), namely the values of H and T, seem realistic for a basaltic crustal composition, samples of high topography with T greater than ~ 60 km appear to be incompatible with a basalt crust due to the basalt-eclogite phase change constraint if they are of significant age. The debate over dating individual provinces within Ishtar is still ongoing. Young and high mountains of pure basalt seem to be in contradiction with an average Venus surface age of ~ 500 Ma (average crater retention age) derived from impact crater density distribution using Magellan imaging [*Phillips* et *al.*, 1992; *Schaber et al.*, 1992]. Indeed, the crater data suggests that the surface has experienced only minor tectonism in this time period [*Schaber et al.*, 1992; *Strom et al., 1994]*. However, it has been suggested that recent tectonic activity has occurred in the compressional belts of Ishtar, especially in Maxwell Montes [*Kaula et al.*, *1992; Solomon et al.*, *1992]*. Ongoing active tectonism is certainly a subject of controversy. For example, *Jull and Arkani-Hamed [1995]*, pointed out that the presence in eastern Maxwell of Cleopatra, a large, almost circular and apparently undeformed impact crater is again in conflict with recent strong tectonism in the area. Indeed, craters of such a large size apparently occur only every 100 Ma or more [*Kaula et al., 1992]. The* ambiguity surrounding Cleopatra and the age of Maxwell was also pointed out by *Kaula et al. [1992],* and *Namiki and Solomon [1993].* Furthermore, laboratory measurements performed recently by *Mackwell et al. [1993;* 1994] showed that under anhydrous conditions, such as may be found in the Venusian crust [*Kaula*, 1990], a very dry diabase is much stronger than the less dry diabase of *Caristan [1982],* originally assumed for Venus' crust *[Smrekar and Solomon, 1992].* A much stiffer crust, with the rheology of a dry diabase, would prevent the highest features in the Ishtar mountain belts from relaxing via gravitational spreading over short time-scales, and instead would allow them to be maintained for several hundred million years [*Smrekar and Solomon, 1992; Arkani-Hamed*, *1995,* submitted]. Based on these observations, and to allow isostatic support by a thickened crust, *Jull and Arkani-Hamed [1995]* suggested that the crust of elevated mountain belts in Ishtar might be highly silicic. This is in fact the case for the continental crest on Earth, and the highlands (anorthosites) on the Moon.

We next consider the Airy model with a crustal density ρ_c = 2700 kg m^{-3} for a more silicic crust *[Vorder Bruegge and Head, 1991].* We find that the silicic crustal density yields the best Airy correlations in the mountain belt areas. On the basis of these results, we conclude that lower elevations (with high GTRs) in Ishtar—with eastern Fortuna as an exception—are supported by a thermal component (strongest in Lakshmi Planum), while the highest elevations (with lower GTRs) are characterized by Airy-compensated crustal thickening. The characteristic elevation for which a cutoff is observed seems to be h ~ 3-4 km.

Support of the higher elevated mountain belt areas (A + F, and M) is best explained by a mostly silicic crust with Airy isostasy. We also include a thermal component for h < 4 km. Horizontal convergence models, involving lateral variations in crustal thickness and thus Airy-type isostasy, were proposed by several workers [e.g. *Crumpler et al.,* 1986; *Head,* 1990; *Roberts and Head, 1990a; Vorder Bruegge and Head, 1991]* for explaining the tectonic origin and evolution of western Ishtar. In this approach, large scale convergence of a thinner crust on a thicker proto-Ishtar (or Lakshmi) results in flexure, buckling, and underthrusting of crust beneath the thicker block. A consequence of this is horizontal regional compressive crustal shortening and thickening which in turn, via isostatic adjustment, induces uplift and thus orogeny (mountain building) *[Roberts and Head,* 1990a; *Vorder Bruegge and Head,* 1991]. *This is* analogous to continental collisions on Earth, such as the Tibet-Himalayas region. Indeed, the Tibetan plateau, with elevation of ~ 5 km [*Bird*, 1978] and similar horizontal dimensions, has been compared to Lakshmi Planum, whereas the Himalayan mountains (peak elevation ~ 9 km), a product of the Indian-Eurasian continental continental plate collision, have been compared to Maxwell Montes [*Kiefer and Hager, 1991; Grimm and Phillips,* 1991 *]. The* trenches in Maxwell and Freyja *[Solomon et al.*, 1992] have been compared by *Kaula et al.* [1992] to the Ganges trough. Using pre-Magellan data *Solomon and Head [* 1990] suggested that the topography at the northern edge of Freyja Montes was a good example of flexural deformation, reminiscent of the outer rise and foredeep of a plate underthrusting a mountain range on Earth [*Sandwell and Schubert,* 1992]. Moreover, *Head [1990]* and *Roberts and Head* [1990a] interpreted the Freyja Montes deformation zone as the product of a continuous sequence involving multiple episodes of convergence, underthrusting of crust from the northern polar plains-Uorsar Rupes region beneath a relatively higher proto-Ishtar/Lakshmi tessera-like block, and crustal imbrication (or accretion) of successively produced crustal slices. The likely support mechanism for the Freyja highlands was assumed by these authors to be Airy compensation of the thickened crust. Analysis of high resolution Magellan SAR images seems to support such interpretations of compressive structures in the Freyja area by underthrusting [*Solomon et al.,* 1991; *Suppe and Connors, 19921. Vorder Bruegge et al.* [1990] proposed that the Maxwell Montes erogenic belt resulted from the horizontal convergence of crust toward Lakshmi, from the east-northeast. *Suppe and Connors [1992]* used Magellan data to infer that in the western slope of Maxwell deformation resulted from the east-directed underthrusting of Lakshmi beneath Maxwell in analogy to terrestrial fold and thrust deformation [*Keep and Hansen,* 1994]. Finally, it was suggested [*Vorder*

Bruegge et al., 1990] that Akna Montes may represent an initial stage of compressional orogeny on Venus.

Thermal isostasy appears to be the dominant support mechanism for the low to medium elevation surface topography observed in Lakshmi Planum (at least up to -3 km), with thermal thinning (to ~ 100 km for a 3 km elevation) of an initially thick (~ 300 - 400 km) ambient thermal lithosphere. Domal structures characteristic of thermal uplift due to basal heating from a rising mantle plume are not observed in Lakshmi, contrary to the broad rises seen in Beta and Atla Regiones [*Kucinskas and Turcotte, 1994].* Thus, if most of the HPE are in the Venus mantle as is the case on Earth, we would favor lithospheric delamination (also called "partial subduction") as the probable source of the thermal surface uplift in Lakshmi. In a delamination event, the lower part of the lithosphere detaches and founders (sinks) into the planetary interior and is replaced by hot mantle material resulting in plateau-shaped uplifts and extensive volcanism *[Bird, 1978, 1979; Houseman et al., 1981; Turcotte*, 1989b; *Nelson,* 1992]. Such a mechanism has been invoked to explain uplift in several areas on Earth, for example the Tibetan and Colorado plateaus [*Bird*, 1978, 1979].

Several pre-Magellan studies *[Head,* 1986; *Roberts and Head,* 1990a, b] used Venera 15 and 16, as well as PVO topography and imagery data to suggest that Lakshmi Planum formed through a combination of crustal underplating (volcanic constructs from intrusive magmatism, or adding low density material from below) and lithospheric delamination. *Head* [1986] noted that the Colette and Sacajawea features (presumably calderas) in Lakshmi maybe associated with lithospheric delamination, combined with compressional deformation in the area. *Kiefer and Hager [1991]* further remarked that the differing amounts of degradation observed at Colette and Sacajawea could be indicative that they formed during different episodes of delamination. This would be an indication that the area has experienced multiple delamination events and associated bursts of volcanic activity.

Thus, one possibility is that the basaltic crust in proto-Lakshmi could have thickened, for example by crustal underplaying and/or horizontal compression as suggested by *Roberts and Head* [1990a, b], while isostatic uplift of this original craton occurred, to the point where its base would have undergone a phase transition to eclogite. Then, the currently observed (h, N) data in Lakshmi could be attributed to the following scenario: The dense (eclogite phase) lower crust becomes gravitationally unstable with respect to the less dense mantle below and, when sufficiently thick, undergoes lithospheric delamination at the level of the basalt–eclogite phase change boundary (as it is likely to be a zone of weakness) by breaking or peeling away into the mantle up to ~ 100 Ma ago. This in turn results in a surface uplift due to thermal expansion and hence would account for the strong thermal isostasy component we see in Lakshmi, while explaining the lava flows which cover the tessera features in this region. However, a fraction of the uplift in Lakshmi could be attributed to Airy isostasy due to the buoyancy of the remaining low-density, thickened basaltic crust, which did not delaminate. Moreover, there could also have been delamination at the base of the silicic crust in the mountain belts, and this could then have propagated into Lakshmi.

In an alternative scenario, thermal isostatic support in Lakshmi could be the result of there having been partial melting of the thickened basaltic crust in this region, due to the presence of radioactive material, in the last ~ 150 My and possibly at present. Indeed, *Jull and Arkani-Hamed [1995]* argued that if the concentration of heat sources (radioactive elements such as uranium, thorium and potassium) measured on the Venus surface by the Venera and Vega spacecraft [*Surkov et al.*, 1984, 1987] is uniformly distributed throughout the basaltic crust, and if the crust thickens more than ~ 50-80 km (depending on the temperature gradient) while being older than ~ 350 Ma, then the higher temperatures generated within the crust may suppress the formation of eclogite. This occurs because if the thickening is very fast, and in view of the transformation time-lag involved in the basalt-eclogite phase transition (- 100 Ma), it is possible to melt the sufficiently thickened basaltic layer before the phase change to eclogite can take place [*Jull and Arkani-Hamed*, *1995]*. This partial melting would in turn induce thermal uplift above the thickened area. Under this scenario (i.e. a strong concentration of HPE in the Venusian crust), the global thermal lithosphere would be expected to be thinner (~ 100 - 200 km) and the mantle cooler, for an

Earth-like mantle viscosity, than in the case of the thick global thermal lithosphere (-300 -400 km) envisaged in the delamination scenario.

Finally, in the Fortuna Tessera province, we view the western part (WF) as a transition zone, with a - 50-50 mix of thermal and Airy isostasy, while the eastern part (EF) would be Airy-compensated basaltic crust. *Kiefer and Hager [1991]* argued that Fortuna Tessera may have experienced multiple delamination events, as they had also suggested for the older pre-existing tessera block presumed to be buried under the volcanic deposits in Lakshmi Planum *[Roberts and Head, 1990a,* b; *Kaula et al.,* 1992]. Indeed, they argue that successive delamination episodes could have led to alternating periods of net upslope and downslope crustal viscous flows, thus possibly explaining the Chevron Tessera landforms in western Fortuna. In fact, the observable in western Fortuna could result from a combination of compressive thickening, as suggested by *Vorder Bruegge and Head [1989],* and delamination. The latter mechanism would account for the thermal isostasy component, perhaps currently partially decayed, we see in the west Fortuna modeling results. *Kaula et al. [1992]* noted that the lower regions of western Fortuna seem less marked by possibly recent tectonic activity and show evidence of volcanism and gravitational relaxation. The topography in the eastern Fortuna area may be in an advanced stage of relaxation due to the strong decay of thermal effects associated with delamination, with the thermal boundary layer (thermal lithosphere) having thickened again via conductive cooling [*Kiefer and Hager, 1991]*. Once again, an alternative mechanism for producing the thermal component in west Fortuna could be the partial melting of the lower crust in this province.

An important question concerns the driving forces responsible for the regional compression which lead to orogenies in the Ishtar mountain belts. On Earth, the prime candidate for such stresses would be slab pull [Schubert, 1980; *Grimm and Phillips, 1991]*. Similar terrestrial orogonies have resulted from crustal thickening in response to continental collisions driven by lithospheric subduction and/or lithosperic delamination. *Grimm and Phillips [1991]* noted that subduction occurring at western Ishtar could drive horizontal motions resulting in convergence in this area. However, these authors believe that if a downwelling is occurring in western Ishtar, then its most likely form is lithospheric delamination. Indeed, they point out that when a portion of the lithosphere delaminates, viscous stresses are exerted by the foundered slabs. Moreover, *Bindschadler and Parmentier [1989]* argued that if a delamination event were sufficiently large, it could initiate large-scale mantle downwelling. Then, if mantle flow was allowed to be coupled with the crust, due to the presence of a ductile lower crust in the Venusian lithosphere, horizontal convergence and crustal thickening could result above the downwelling area, leading to uplift in Lakshmi, as well as compressional deformation associated with orogeny [*Roberts and Head*, *1990* a, b]. Each of these subduction scenarios, whether full or partial (delamination), has problems reproducing all the features observed in Ishtar if considered alone [Roberts *and Head,* 1990 a, b], so they would probably have to operate in combination with other mechanisms (e.g. crustal underplaying for Lakshmi). Finally, *Jull and Arkani-Hamed [1995]* suggested that the mountain belts surrounding Lakshmi might have formed from the collision of silicic cratons drawn together by a downwelling in this region.

The analysis of compensation in the Ishtar highlands given in this paper . supports a thick, strong reference lithosphere on Venus, with isostatically supported topography. A thick (~ 300 - 400 km) global thermal lithosphere is consistent with the suggestion of episodic global subduction events on Venus and the associated non-steady-state planetary thermal evolution mechanism. A thinner (- 100-200 km) global thermal lithosphere would be more in agreement with quasi-steady state thermal evolution models which predict monotonic decline for geodynamic activity on Venus. A major result of the Magellan mission was the observation that the global impact crater population on Venus is characterized by a near random (Poisson) statistical distribution [*Phillips et al.,* 1992; *Schaber et al.,* 1992; *Strom et al.,* 1994] with an average surface age of ~ 500 Ma for the planet. Based on these radar imaging observations, *Schaber et al.* [1992] postulated that a global catastrophic resurfacing event must have occurred on Venus ~ 500 ± 300 Ma before present (BP) and that following this episode the global Venusian lithosphere stabilized. Namely, that global tectonic and surface volcanic activity are small since the resurfacing event and have only played a minor role in vertical heat transport since ~ 500 Ma ago.

Arkani-Hamed and Toksoz [1984], *Arkani-Hamed [1994],* and *Turcotte* [1993] each proposed basic models for the extraction of heat from the planetary interior, which could account for catastrophic volcanic resurfacing, followed by a sharp decline in surface tectonic and volcanic activity and heat flux. Using 3-d convection models to calculate planetary thermal evolution, *Arkani-Hamed and Toksoz* [1 *984],* and *Arkani-Hamed [1994]* propose that, throughout most of its history, Venus was subjected to an oscillatory convective regime, resulting in episodic global resurfacing with the convective style finally changing from cyclic to quasi-steady-state ~ 500 Ma BP. The associated episodic recycling of the crust in this model induces rapid planetary (interior) cooling, which in turn results in progressive solidification of the planet's core. This then leads to the disappearance of the magnetic field, while the cooling of Venus' interior leads to an increase in viscosity and thus a decreasing Rayleigh number. Ultimately, the convective regime (and associated heat flow) changes from oscillatory to quasi-steady-state motion about ~ 500 Ma ago in association with the growth of a buoyant, viscous, one-plate crust/lithosphere; this stops the recycling of the surface at the same epoch *[Grimm,* 1994a; *Strom et al., 1994].* Hence, in Arkani-Hamed's model, the planet "freezes-in" a one-plate rigid upper boundary layer due to secular heat loss, while tectonic activity is significantly reduced even though the underlying mantle is still convecting. Tectonism and thermal release would thus currently be in a state of slow monotonic decline. *Arkani-Hamed*'s *and Toksoz's* model [1984] assumed that ~ 90% of the HPE are located in the Venusian lithosphere, with essentially all heat being conducted through the crust to the surface once the interior has cooled due to secular heat loss. In the more recent version of this model [*Arkani-Hamed*, 1994], the author obtains similar results for heat sources with chondretic concentration distributed throughout the mantle. However, for both models, the quasi-steady-state balance of interior and lithosphere are associated with a relatively thin global thermal lithosphere (-100 -200 km) and a cool mantle.

Alternatively, *Turcotte [1993]* assumed that most of Venus' radiogenic sources are located in its mantle, in analogy to the Earth. Turcotte proposed that heat loss from the interior of Venus has been, and is still, strongly time-dependent (i.e. non-steady-state) and is associated with episodic (i.e. cyclic) subduction events. In this model, the last global resurfacing event (~ 500 Ma BP) was accompanied by strong heat loss from the interior through widespread and rapid subduction (hence, recycling of the crust into the mantle). Then, with the mantle heat flux greatly reduced, the lithosphere was free to cool and thicken conductively during the past ~ 500 Ma. Simultaneous] y, the mean mantle temperature started to increase again, inducing more vigorous mantle convection and plume flux. Ultimately, breakup of the lithosphere will occur, followed by another episode of global catastrophic subduction and associated volcanic resurfacing. The thick thermal lithosphere (~ 300 km n ~ 500 Ma) predicted by this catastrophic cyclic model is in good agreement with estimated parameter values for the isostasy models investigated in this papeı (in particular the thermal thinning), and is capable of supporting the high topography and associated gravity/geoid anomalies observed in Ishtar.

Conclusions

Using Magellan altimetry and gravity data, our analysis has shown that topography in Ishtar Terra is substantially compensated. Also, the geoid-topography correlations observed in each of the Ishtar subregions can be reproduced by isostasy models involving variations in crustal thickness (Airy) and/or lithospheric thickness (via thinning of the thermal lithosphere) provided Venus has a thick ambient thermal lithosphere (-300 -400 km). These results are in agreement with those obtained by *Kucinskas and Turcotte [1994]* for the equatorial highlands.

Lower elevations (h <3-4 km), associated with high GTRs, in the erogenic belts, Lakshmi Planum, and western Fortuna Tessera seem to be associated with a thermal compensation component; this is especially strong in Lakshmi (highest GTR in Ishtar). Thermal support of 3 km of topography in Lakshmi requires thinning of the background lithosphere (~ 300-400 km) to ~ 100 km. The higher elevation areas (h > 4 km), with low GTRs, are probably associated essentially with Airy isostasy. However, Airy crustal thicknesses in excess of 60 km are required to support the highest topography in the mountain belt areas. Due to the basalt-eclogite phase change, this suggests that crustal composition in the mountains may be silicic, if these structures are more than -25-50 Ma old, There seems to be a decay in thermal compensation associated with a significant decrease in GTR from west to east in Ishtar. The zero-elevation basaltic crustal thickness of ~ 24 km, obtained for the mostly Airy-compensated sample in eastern Fortuna Tessera, is compatible with values derived by *Grimm [* 1994b] for the background crustal thickness in the Venusian plains from his study of compensation in the Venusian plateaus.

Our study also supports previous suggestions [e.g. *Roberts and Head, 1990a; Smrekar and Solomon,* 1992] that one should invoke a mix of basic tectonic model components, possibly operating in successive evolutionary phases, to explain the complex tectonic origin and evolution of the Ishtar Terra highlands. Among various possible combinations of processes for the formation of Ishtar, and within the framework of our isostatic approach to compensation, we would favor horizontal crustal convergence and underthrusting for the mountain areas, in association with full and/or partial subduction as the driving force. To account for the strong thermal isostasy component we see in Lakshmi

Planum one possibility is to envisage one (or more) delamination event(s) for a thickened basaltic crust which may have transformed into eclogite. The decrease in thermal compensation we observe in the Fortuna Tessera province (west to east) may also be associated with one (or several) episode(s) of delamination. Delamination could still be partially active in west Fortuna, with a partially relaxed topography, whereas it would have terminated some time ago in eastern Fortuna, where the thermal lithosphere has had sufficient time to thicken again, towards its ambient value, while the topography relaxed. However, if the measured surface concentration in radioactive heat sources were applicable throughout the basaltic crust, then the formation of eclogite at depth could be effectively suppressed and the thermal component of surface uplift in Lakshmi and in west Fortuna could be the product of partial melting of the thickened crust in these areas.

The results of this long-wavelength study of isostasy in Ishtar (in particular the inferred strong, thick thermal lithosphere), are consistent with observational evidence including extremely high topography, associated gravity (geoid) anomalies, unrelaxed craters [*Grimm and Solomon, 1988]*, and the steep slopes in the Maxwell area, as well as with the thick elastic lithosphere (~ 40 km) derived from short wavelength flexural studies [*Sandwell and Schubert*, 1992; *Phillips* 1994]. A thinner (~ 100-200 km) background thermal lithosphere, with a large fraction of the HPE on Venus residing in the crust, would be compatible with a cool mantle and a quasi-steady-state thermal evolution, as suggested by *A rkani-Hamed [1994]*. On the other hand, if the thick (- 300-400 km) background thermal lithosphere implied by our thermal isostasy modeling results is indeed prevalent on Venus, then this is more in agreement with the predictions of catastrophic cyclic global geodynamic models, associated with strongly unsteady-state thermal evolution and a hot mantle, such as *Turcotte's [1993]* episodic model for subduction on Venus.

Further work to test these hypotheses will be necessary. Higher degree and order (≥ 90) harmonic solutions for the Venus geopotential may soon become available [*Konopliv and Sjogren*, 1995, personal communication], exploiting the Magellan circular orbit gravity data set to its fullest potential. These new high resolution models will yield improved regional gravity and geoid data values for even better modeling results. They may also allow for more reliable estimates of the Venusian tidal Love number k_2 (measuring the response of the solid planet to tidal interactions), which is an indicator of core fluidity [*Yoder*, 995]. A solid core (lower k_2 value) could be evidence for a currently cold mantle in quasi-steady-state with a thermal and geodynamic evolution of Venus in monotonic decline (since about 500 Ma ago). A fluid outer core (higher k_2 value), however, would be evidence in favor of a hotter Venusian mantle, rich in HPE, more in agreement with a strongly time-dependent thermal evolution associated with episodic tectonism. Then, the Venus mantle would be currently heating up, allowing for a future global resurfacing outburst to take place.

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Table 1. Parameters for Regional Model Fits with 2° x 2° Data Sampling, and ρ_c = 2900 kg m^{-3}

Region	h_{max} km	C x 100 %	GTR m/km	W km	σ_{Pratt}	H km	T(h_{max}) km	σ_{Airy}	h^{th}_{max} km	y_{L_0} km	$y_L(h_{max})$ km	σ_{th}
Greater Ishtar	8.0	86.5	11.3	144	15.5	66.0	124	15.7	3.0	272	N/A	25.1
Lakshmi	3.0	87.8	19.9	256	10.0	126	148	9.9	4.2	381	106	11.5
Akna + Freyja	4.8	80.7	12.5	160	8.4	69.5	104	8.3	3.8	345	N/A	12.2
Maxwell	8.0	83.1	7.6	97.3	6.4	24.6	82.6	7.8	4.4	404	N/A	24.1
West Fortuna	4.0	88.2	7.6	98.1	12.7	35.8	64.8	12.6	3.1	285	N/A	16.1
East Fortuna	2.0	98.8	4.1	52.7	11.2	23.8	38.3	11.3	1.1	102	N/A	10.7

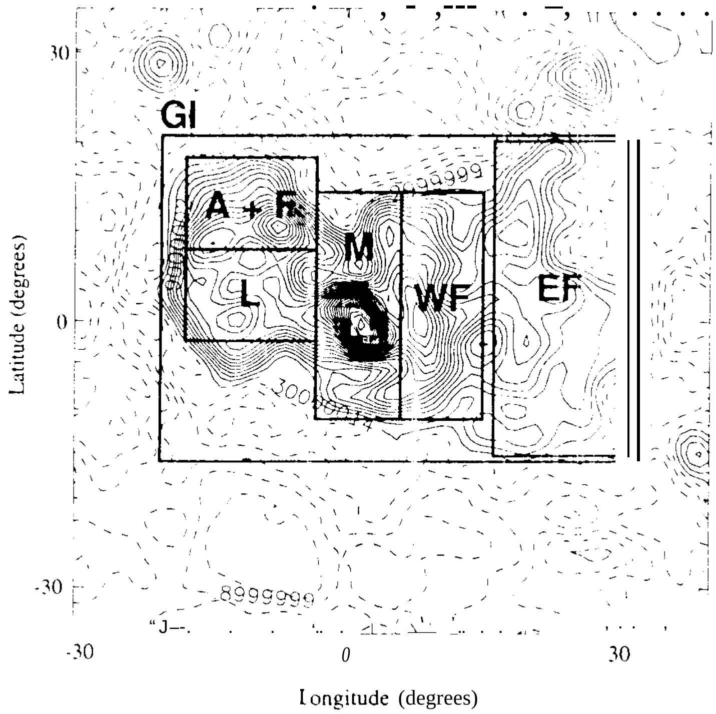
Figure Captions

Figure 1. Contour maps of topography variations (a) and geoid anomalies (b), for the Ishtar Terra area in a rotated coordinate system (with Maxwell Montes at 0° longitude, 0° latitude). Contour intervals are 0.3 km for the topography, and 5m for the geoid. The black rectangles in (a) and (b) outline the regions studied in this paper, (see text).

Figure 2. Scatter plots of Bouguer anomaly (BA) versus gravity for an uncompensated topography (Δg^u) for the six regions considered in this work. The open circles correspond to the 2° x 2° sampled data points. The solid lines are best-fit linear correlations with the slope yielding a degree of compensation in each considered region.

Figure 3. Scatter plots of geoid anomaly (N) versus height anomaly (h) for the six regions considered in this paper. Anomalies are determined with respect to a reference sphere of radius R_0 = 6051.848 km (mean planetary radius of Venus). Open circles are 2° x 2° sampled data points. The solid curves are best-fit theoretical correlations for the Pratt (a), Airy (b), and thermal (c) isostasy models.

a) Topography Variations Over Ishtar Terra



b) Geoid Anomalies Over Ishtar Terra

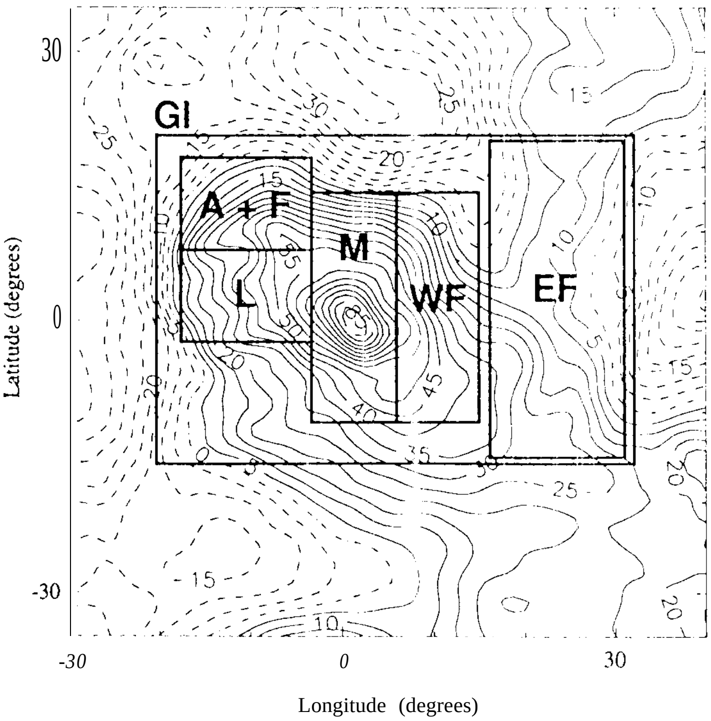


Figure 1.

Regional Compensation

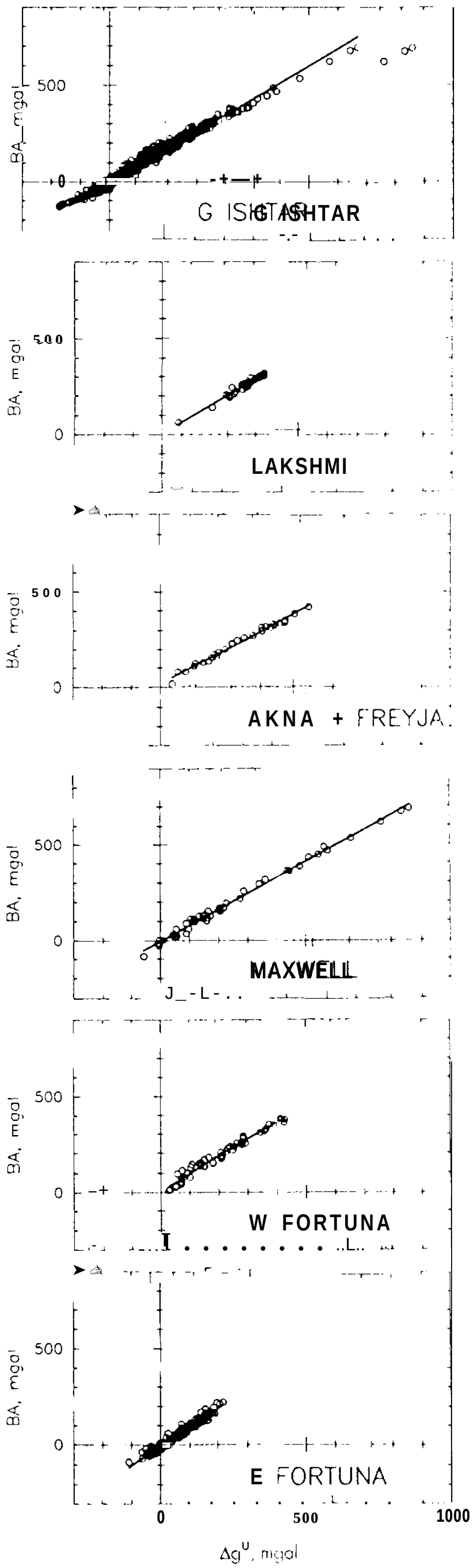


Figure 2.

a) Pratt b) Airy c) Thermal

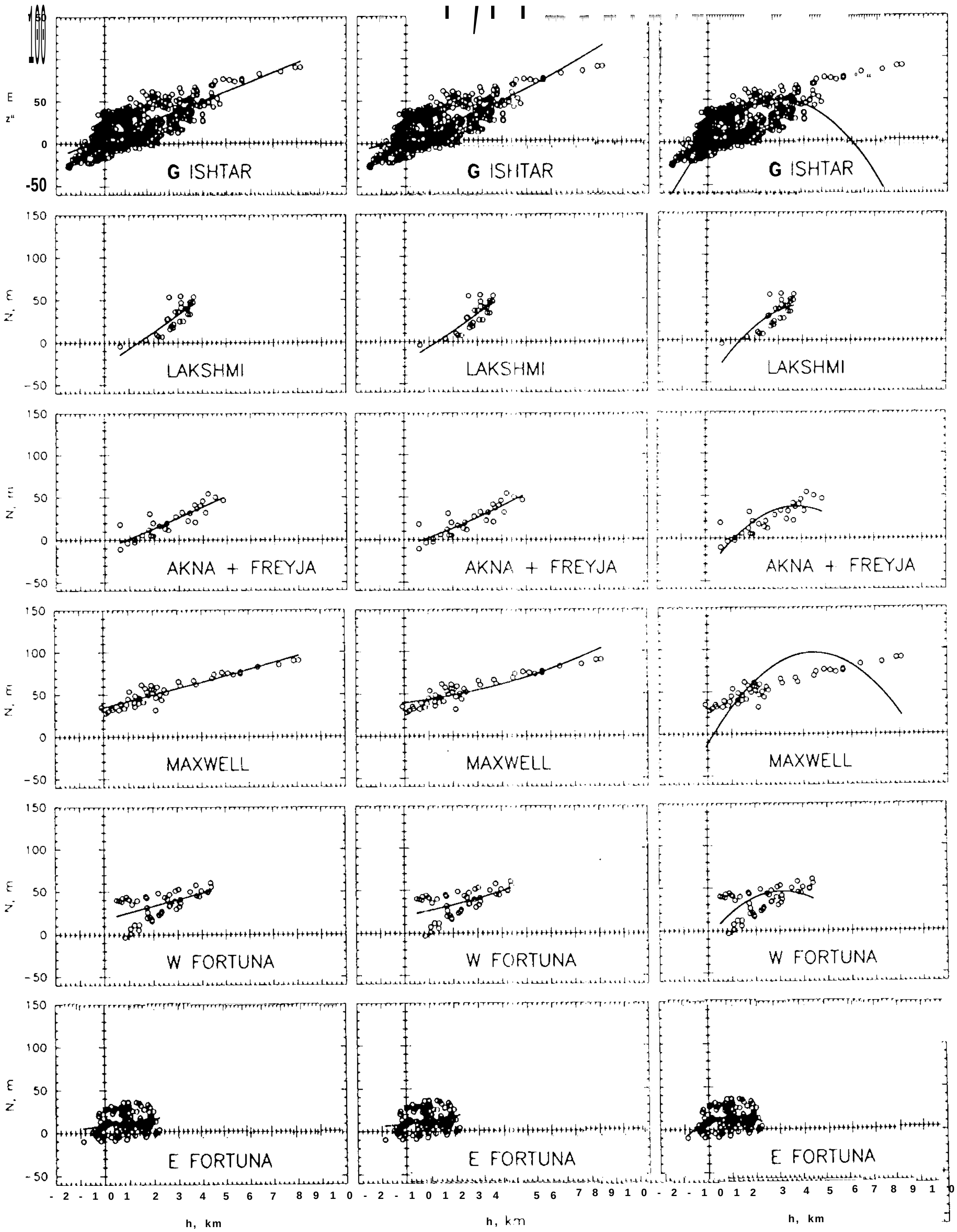


Figure 3.