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LITHOSPHERIC FLEXURE BENEATH THE FREYJA MONTES FOREDEEP, VENUS: CONSTRAINTS ON LITHOSPHERIC THERMAL GRADIENT AND HEAT FLOW

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Abstract. Analysis of Venera 15 and 16 radar images and topographic data from the Freyja Montes region on Venus suggest that this mountain belt formed as a result of a sequence of underthrusts of the lithosphere of the North Polar Plains beneath the highlands of Ishtar Terra. The Freyja Montes deformation zone consists, south to north, of a linear orogenic belt, an adjacent plateau, a steep scarp separating the plateau from the North Polar Plains, a linear depression at the base of the scarp, and an outer rise. The topographic profile of the depression and outer rise are remarkably similar to that of a foreland deep and rise formed by the flexure of the underthrusting plate beneath a terrestrial mountain range. We test the lithospheric flexure hypothesis and we estimate the effective thickness T_e of the elastic lithosphere of the underthrusting portion of the North Polar Plains by fitting individual topographic profiles to deflection curves for a broken elastic plate. The theoretical curves fit the observed topographic profiles to within measurement error for values of flexural rigidity D in the range (0.8-3) $\times 10^{22}$ N m, equivalent to T_e in the range 11-18 km. Under the assumption that the base of the mechanical lithosphere is limited by the creep strength of olivine, the mean lithospheric thermal gradient is 14-23 K/km. The portion of the North Polar Plains to the immediate north of Freyja Montes stands at a regional elevation very near the modal elevation for the planet, so the inferred elastic lithosphere thickness and thermal gradient may be at least approximately representative of a significant fraction of the Venus lithosphere. That the inferred thermal gradient is similar to the value expected for the global mean gradient on the basis of scaling from Earth provides support for the hypothesis that simple conduction dominates lithospheric heat transport on Venus relative to lithospheric recycling and volcanism.

INTRODUCTION

The heat budget of the planet Venus is poorly known. On the basis of the ^{40}Ar abundance in the atmosphere [*Hoffman et al.*, 1980] and the U,Th, and K concentrations in surface soils [*Surkov et al.*, 1987], heat production within Venus has been commonly scaled from estimates for the Earth. Under the assumption that Venus presently loses heat at the same rate per mass as the Earth, the heat flux is 74 mW/m^2, and the average vertical thermal gradient in the lithosphere is 20-25 K/km if conduction is the dominant heat transport mechanism in the outer layer of the planet [*Solomon and Head*, 1982]. It is important to seek tests of the premise that heat flux on Venus may be scaled from the Earth. One means to do so is to determine the thickness of the elastic lithosphere on Venus from the flexural response to surface loads, since the lithospheric thickness is limited by the temperature-dependent depth at which ductile behavior dominates brittle behavior at flexural strain rates [*Goetze and Evans*, 1979]. A few estimates of the elastic lithosphere thickness beneath Eisila and Bell Regiones have been reported from gravity anomaly modeling [*Cazenave and Dominh*, 1981] and topographic considerations [*Janle et al.*, 1988], but questionable assumptions made in these analyses render these estimates suspect [*Reasenberg and Bills*, 1983; *Solomon and Head*, 1990].

An additional opportunity to estimate elastic lithosphere thickness is afforded by the Freyja Montes region of Ishtar Terra. Analysis of Venera 15 and 16 radar images and topographic data suggest that this mountain belt formed as a result of a sequence of southward underthrusts of the lithosphere of the North Polar Plains beneath Ishtar Terra [*Head*, 1990]. To the north of a steep boundary scarp 1-3 km in height is a closed depression several hundred meters deep [*Kuz'min et al.*, 1987]. In cross section the topographic profile of the depression [*Head*, 1990] is remarkably similar to that of a foreland deep formed by the flexure of the underthrusting plate beneath a terrestrial mountain range [e.g., *Karner and Watts*, 1983; *Royden*, 1988]. While terrestrial foredeeps are typically filled with sediments, the much lower rates of erosion and sedimentation on Venus and limited infilling by young volcanic deposits [*Head*, 1990] have apparently left the flexural signature of the topography at least partially intact. In this paper we compare quantitatively the Freyja Montes foredeep topographic profile with that for a flexed underthrust plate, and on the basis of this comparison we constrain the elastic lithosphere thickness and thermal gradient beneath the North Polar Plains.

The portion of the North Polar Plains to the immediate north of Freyja Montes stands at a regional elevation [*Kuz'min et al.*, 1987] very near the modal elevation for the planet [*Ford*, 1986]. Some 60% of the surface of Venus stands at an elevation within 500 m of this modal value [*Pettengill et al.*, 1980]. To the extent that regional elevation in such plains areas is, to first order, a measure of lithospheric thermal gradient [*Morgan and Phillips*, 1983], the thickness of the elastic lithosphere derived for the underthrusting portion of the North Polar Plains may be at least approximately representative of a significant fraction of the Venus lithosphere. By this line of reasoning the inferred thermal gradient provides an important constraint on heat flow in the areally extensive plains regions, and thus on modes of lithospheric heat transport on the planet [*Solomon and Head*, 1982].

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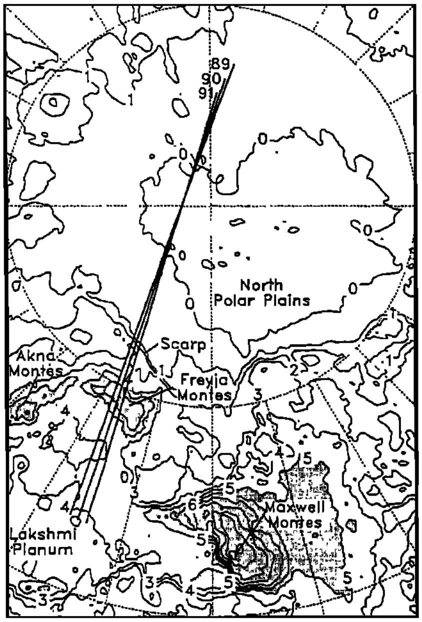

Fig. 1. Altimetric map of the Freyja Montes region, showing the Venera 15 and 16 tracks along which profiles are used to infer elastic lithosphere thickness. Elevation is with respect to a 6051-km-radius sphere. Contours, in km, are from a compilation of Pioneer Venus and Venera 15 and 16 altimetry data by E. Eliason, U.S. Geological Survey. Regions higher than 5 km are shaded.

GEOLOGICAL EVIDENCE FOR UNDERTHRUSTING

The Freyja Montes deformation zone consists, south to north, of a distinctive linear orogenic belt, an adjacent plateau, a steep scarp separating the plateau from the North Polar Plains lying about 3 km below the plateau, a foredeep at the base of the scarp, and an outer rise (Figures 1 and 2). On the basis of radar images and topography, the Freyja Montes deformation zone has been interpreted to be the site of large-scale convergence of crustal blocks and underthrusting of the North Polar Plains beneath Ishtar Terra [*Head*, 1990]. The lineated topography, the asymmetry in across-strike topographic profile, the associated linear troughs and ridges interpreted to be anticlines and synclines on Freyja Montes and the adjacent plateau, and the strike of the steep northern boundary scarp are all consistent with significant compressional strain oriented N10°-15°E. Evidence for underthrusting of the North Polar Plains beneath Ishtar Terra includes the distinctive change in topography at the scarp marking the boundary between plains and plateau, the narrow foredeep and associated outer rise, and the series of apparently imbricated segments making up the plateau between the linear mountain belt and the foredeep.

ELASTIC LITHOSPHERE THICKNESS

We may test quantitatively the hypothesis that topographic profiles of the foreland deep and outer rise north of Freyja Montes are consistent with lithospheric flexure. On the basis of such a test we may estimate the effective thickness T_e of the elastic lithosphere of the underthrusting portion of the North Polar Plains. To conduct this test and to estimate T_e we fit individual topographic profiles (Figure 2) to deflection curves for a broken elastic plate [*Turcotte and Schubert*, 1982]:

$$w = (V \alpha^3 / 2 D) \exp(-x/\alpha) \cos(x/\alpha) \qquad (1)$$

where w is the deflection, D is the flexural rigidity, V is the vertical load applied to the end of the plate at the horizontal position x = 0, and α is the flexural parameter given by $\alpha^4 = 4 D/(\rho_m g)$, where ρ_m is the density of mantle material and g is the gravitational acceleration. Free parameters in the fit are α, V, and the horizontal origin. The elastic lithosphere thickness is derived from α by means of the relation $D = E T_e^3/[12(1 - \nu^2)]$, where E and ν are the Young's modulus and Poisson's ratio of the elastic lithosphere, respectively.

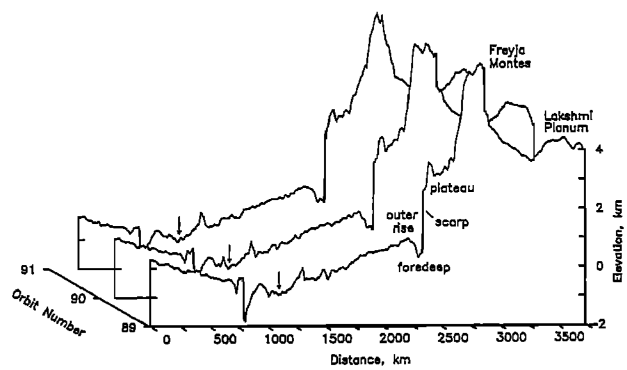

Fig. 2. Topographic profiles across the North Polar Plains and Freyja Montes (Venera 15 and 16 orbits 89-91), with the locations of the northern boundary scarp, foredeep, and outer rise labeled. Profiles are aligned at the points corresponding to the northern culmination of the orbits (arrows). Data are courtesy of the Academy of Sciences of the U.S.S.R., Institute of Radioengineering and Electronics.

The principal source of uncertainty in estimating α arises from errors in the zero datum for deflection after correcting for the long-wavelength topography of the North Polar Plains. For all of the Venera 15/16 orbits yielding topographic data for this region (orbits 85-91), there is a pronounced linear slope to the topographic profile between the Freyja Montes foredeep and the point on the profile corresponding to the northern culmination of the orbit (Figure 2); the opposite-side data display a long-wavelength linear slope of opposite sign, with the break in slopes approximately coinciding with the culmination point. All of these data are from locations northward of Pioneer Venus altimetry coverage [*Pettengill et al.*, 1980]. Whether these persistent linear slopes are artifacts of data reduction or reflect a long-wavelength heterogeneity in structure, we presume that the flexural signature of underthrusting occurs dominantly at shorter scales. We have therefore removed from the topographic profiles a linear trend (of slope 1.6×10^{-3}) obtained by least squares from the portion of each profile between the orbit culmination point and a position 250 km northward of the Freyja Montes foredeep. Three such profiles are shown in Figure 3.

The topographic profiles, corrected for long-wavelength slope, have been fit to equation (1) by minimizing the root mean squared (rms) misfit. To account for the nonlinearity of the parameter fitting, we conducted a systematic grid search in three-dimensional parameter space to find the best-fitting combination of α, V, and horizontal origin. The theoretical flexure profiles fit the observed topography to within an rms misfit of about 50 m (Figure 3), a figure comparable to the nominal error in relative along-track elevation at short wavelength in the Venera data [*Kuz'min et al.*, 1987]. The hypothesis of lithospheric flexure induced by underthrusting is thus quantitatively consistent with the topography.

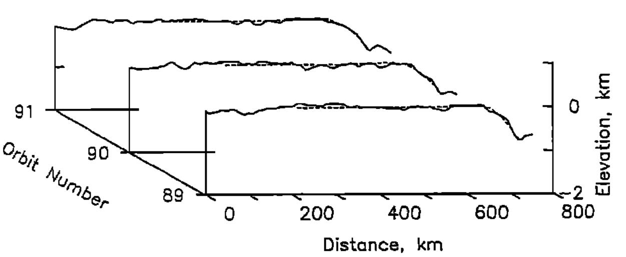

Fig. 3. Portions of the topographic profiles from Figure 2, after correcting for long-wavelength slope (solid lines). Also shown are model profiles (dashed lines) for flexure of a uniform plate subjected to an end vertical load (see text). Profiles are aligned at 80°N; the origin of the distance scale differs from that of Figure 2.

The best-fitting values for the flexural parameter α for the three profiles (orbits 89-91) with the best-developed signature of the foredeep are in the range 37-52 km. These values were derived from the actual profiles (Figure 3), which are along orbit tracks that make an angle of about 60° with the strike of Freyja Montes, the northern boundary scarp, and the foreland deep (Figure 1). Before converting to other parameters they should thus be multiplied by the sine of this angle; i.e., α = 32-45 km. This corrected range in α corresponds to flexural rigidity D in the range (0.8-3) $\times 10^{22}$ N m. To convert flexural rigidity to T_e we take $\nu = 0.25$ and $E = 60$ GPa, values appropriate to terrestrial oceanic lithosphere [e.g., *Bodine et al.*, 1981]. With these values the elastic lithosphere of the underthrusting portion of the North Polar Plains is 11-18 km thick. While the effective value of E for the elastic lithosphere of Venus is uncertain to within perhaps a factor of 2, the contribution to the fractional uncertainty in T_e is only about ± 25%, comparable to the spread in derived values.

THERMAL GRADIENT

These values of T_e may be converted to the mean lithospheric thermal gradient, given a representative strain rate and a flow law for ductile deformation of material in the lower lithosphere. This conversion is accomplished by constructing models of bending stress consistent with the strength envelope and finding for each model the equivalent elastic plate model having the same bending moment and curvature [*McNutt*, 1984]. The brittle portion of the strength envelope is taken from the low-pressure friction law of *Byerlee* [1978], with a lithostatic pressure gradient appropriate to the Venus crust (27 MPa/km). We take 10^{-16} s^{-1} as the representative strain rate, and we assume that ductile flow in the lower lithosphere is limited by the creep strength of olivine [*Goetze*, 1978], on the basis of the inference from the depths of impact craters and the characteristic spacing of tectonic features that the crust beneath plains units on Venus is no more than 10-20 km thick [*Zuber*, 1987; *Banerdt and Golombek*, 1988; *Grimm and Solomon*, 1988]. The surface temperature is taken to be 740 K, and the lithospheric thermal gradient dT/dz is taken to be vertically uniform. The conversion from T_e to T_m and dT/dz as a function of curvature is illustrated in Figure 4.

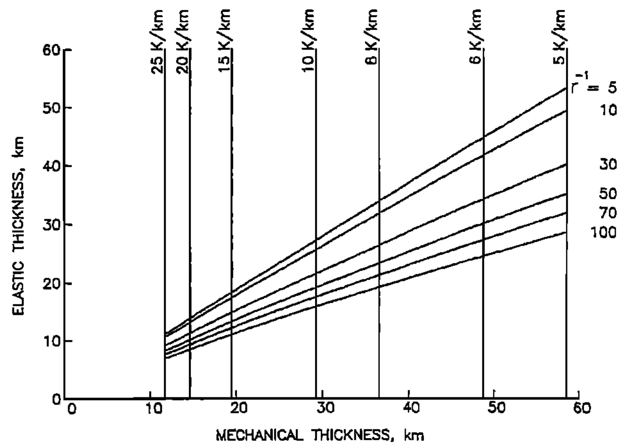

Fig. 4. Conversion of elastic lithosphere thickness T_e to mechanical lithosphere thickness T_m and lithospheric thermal gradent dT/dz as functions of curvature r^{-1} (in units of 10^{-8} m^{-1}), after *McNutt* [1984]. Mean thermal gradients shown correspond to a strain rate of 10^{-16} s^{-1}.

The curvature at the zero crossings of the flexural profiles for the uniform elastic plate model (e.g., Figure 3) is (1-2) $\times$ 10^{-7} m^{-1}. The corresponding surface horizontal extensional strains and stresses are about 1×10^{-3} and 70 MPa, respectively. From Figure 4, values of 11-18 km for T_e are equivalent to mean lithospheric thermal gradients of 14-23 K/km. For a characteristic lithospheric thermal conductivity of 3 W/m-K, the heat flux is 50-70 mW/m^2. These values would be modified somewhat if between strong upper crustal and upper mantle layers there is a weak lower crustal layer with strength limited by ductile flow.

IMPLICATIONS

The flexural topographic profile of the Freyja Montes foredeep is thus consistent with a lithospheric thermal gradient (14-23 K/km) similar to that expected for the global mean gradient on the basis of scaling from Earth [*Solomon and Head*, 1982]. As noted earlier, the elevation of the North Polar Plains to the immediate north of the foredeep and associated outer rise [*Kuz'min et al.*, 1987] is similar to the modal elevation of Venus [*Ford*, 1986] and to the elevation of widespread plains units elsewhere on the planet. A reasonable inference, therefore, is that a comparable gradient characterizes the lithosphere beneath other plains regions of Venus at similar elevations [e.g., *Morgan and Phillips*, 1983]. This inference provides independent support for the hypothesis [*Kaula and Phillips*, 1981; *Grimm and Solomon*, 1987] that simple conduction dominates lithospheric heat transport on Venus, i.e., that neither lithospheric recycling nor volcanism are the principal mechanism of internal heat loss (although either process may be important for crustal formation and evolution).

The Magellan mission to Venus will offer the opportunity to test and to extend considerably the inferences made here. The interpretation of the topographic profiles of Figure 3 in terms of lithospheric flexure leads to the prediction of near-surface horizontal extensional stresses of 50-100 MPa in the outer wall of the foredeep. Such stress levels should have given rise to the formation of extensional tectonic features with strike directions parallel to the trend of the foredeep and outer rise. Evidence for such features should be sought in Magellan radar images of this region, although there is a possibility that a regionally compressive stress field may mask the near-surface flexural stresses. Further, Magellan imaging and altimetry data should yield many more examples of lithospheric flexure in other areas of underthrusting and in response to vertical loading (e.g., by volcanoes). A prediction of the thermal isostasy model [*Morgan and Phillips,* 1983] for variations in regional elevation among plains areas is that the mechanical lithosphere thickness should be comparable in regions at similar elevations. Significant lateral variations in elastic lithosphere thickness can also be expected, however, in the vicinity of major volcanic centers and regions of mantle upwelling. Both hot-spot [e.g., *Kiefer and Hager,* 1988] and crustal divergence [e.g., *Head and Crumpler,* 1987] models for the equatorial highlands, for instance, lead to specific laterally variable thermal structures potentially testable by the procedures followed here.

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