ESTIMATES OF ELASTIC LITHOSPHERE THICKNESS AND HEAT FLUX BENEATH LARGE VOLCANOES ON VENUS; Patrick J. McGovern, Mark Simons, Dept. of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139, and Sean C. Solomon, Dept. of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C. 20015.

Introduction. A fundamental unknown on Venus is the global heat flux. The heat flux cannot be measured directly on Venus, but the thermal gradient may be inferred indirectly from the thickness of the elastic lithosphere. To this end, we calculate gravity/topography admittances in the harmonic domain for nine large volcanoes on Venus. We compare the observed admittances to those calculated from a thin elastic spherical shell flexure model in order to estimate the elastic plate thickness supporting the volcanoes. We convert elastic plate thickness to mechanical plate thickness, and then estimate the thermal gradient and heat flux. The resulting heat flux values are lower than those calculated by scaling Earth's heat flux to Venus [1]. We also note that mechanical plate thickness estimates at volcanoes are generally higher than those found at coronae [2].

Data and Analysis. The admittance is the transfer function between gravity and topography, determined in a linear least squares sense. We use the latest available versions of spherical harmonic representations of the gravity (from field MGNP75H [3]) and topography [4] fields of Venus. We employ the method described in [5] to generate global maps of admittance variations. The admittance is a function of the spherical harmonic degree band included in the integration, and is spatially localized by restricting the domain of integration to a spherical cap. The cap diameter is set to be slightly larger than the longest wavelength in the chosen harmonic degree band. The cap is translated over the surface of Venus to generate the global admittance maps [5], from which we select individual values for several large volcanoes.

We compare the observed admittances to those calculated for flexure due to surface loading of a thin elastic spherical shell [6]. For a given volcano, we determine the elastic plate thickness T_e that best predicts the observed admittance value. The admittance is a function of the depth to a compensating density contrast, here taken to be crustal thickness T_c, as well as of the elastic plate thickness T_e We estimate T_e using a nominal crustal thickness of 25 km, as determined from local and global geoid/topography admittances [5]; larger crustal thickness values will result in smaller T_e estimates and vice versa (the slope of this tradeoff is typically 1 km in T_e for every 4 km in T_c). These estimates are derived over a band of spherical harmonic degrees $l = 42$ to 55 (wavelengths 900 to 700 km). Formal errors in T_e are typically 3 to 5 km. To obtain an estimate of the depth to which appreciable stresses are supported in the lithosphere, the elastic plate thickness must be corrected for the effect of finite yield strength of the lithosphere [7]. This correction, which depends on plate curvature, yields the mechanical plate thickness T_m. In terrestrial applications, it has been recognized that small values of plate curvature typical at seamounts (compared to those at subduction zones, for example) result in negligible corrections [8], so we can set $T_m \approx T_e$ The thermal gradient is then estimated from the known surface temperature (500° C) and the temperature at the base of the mechanical lithosphere. The latter temperature is here taken here to be 750° C, but this quantity depends on the flow law and the characteristic strain rate at the base of the lithosphere, and is uncertain to perhaps ± 100° C. We obtain the heat flux q by multiplying the thermal gradient by the thermal conductivity appropriate for near-surface rocks (3 W/m°K [9]). Considering all sources of error, the heat flux has an uncertainty of as much as a factor of 2.

Results. In Atla Regio, Maat and Ozza Montes yield values $T_m \approx 50$ km, $q \approx 15$ mW/m^2; Sapas Mons gives a lower value for mechanical thickness $T_m \approx 35$ km, with correspondingly higher $q \approx 21$ mW/m^2. Volcanoes in Western Eistla Regio (Sif and Gula Montes) and Eastern Eistla Regio (0.5°N 34.5°E and 9°N 29°E) yield similar values $T_m \approx 40$ km, $q \approx 19$ mW/m^2. A volcano southwest of Beta Regio (10° N 275° E) gives results similar to the Eistla volcanoes. The T_m estimate for a large volcano at 29°N 49°E in southern Bell Regio (15 km, $q \approx 50$ mW/m^2) is not well constrained; within the calculated error bounds, the admittance is consistent with compensation by a plate of thickness 0 km (the limiting case of Airy isostasy) to 20 km. We have included Nefertiti Corona (in northern Bell Regio) for comparison with the volcanoes. The T_m estimate for Nefertiti (20 km, $q \approx 38$ mW/m^2), is in the range calculated for other coronae [2], and significantly lower than that for the volcanoes considered here (except for its neighbor at 29°N 49°E). We note that volcanoes in a given region tend to have similar values of T_m. This observation is consistent with the expectation that lithospheric properties should be broadly similar across a region, and is an indication that the analysis is robust. The T_m estimates presented here agree well with those calculated independently by the integration of bandpassed gravity and topography anomalies (the "effective density" method [10]).

Discussion. The heat flux values obtained at these volcanoes are smaller than values obtained by scaling the Earth's heat flux to Venus [1, 11]. One possibility is that the scaling argument is not strictly correct. However, chemical analysis of the surface of Venus by Venera landers indicates that the inventory of radiogenic heat-producing elements is broadly similar to that of Earth [12]. The scaling should therefore hold to within perhaps a factor of 2. Alternatively, temporal variations of heat flux could account for the discrepancy. By this view, removal of internal heat would be accomplished mainly during periods of high heat flux, presumably accompanied by increased rates of volcanism and tectonism. Such periods would alternate with periods of low heat flux, with correspondingly reduced rates of volcanism and tectonism, during which a small fraction of internal heat is removed. Such a scenario has been invoked to explain the distribution of craters on the surface of Venus [e.g. 13, 14]. We can estimate the thickness of the thermal lithosphere by assuming a value for temperature at its base (assumed to be 1250° C) and dividing the difference between that and the surface temperature by the thermal gradient, yielding a thermal boundary layer thickness for the above volcanoes in the 100-150 km range. This is considerably lower than the 300 km thickness [14] predicted by conductive cooling of a half-space over the past 300 to 500 My (the average surface age of the venusian plains).

Estimates of T_m for the large volcanoes studied here are significantly larger than those estimated for all but a handful of the largest coronae [2]. This observation, coupled with the documented difference in average surface age between volcanoes and coronae [15, 16], suggests that formation of volcanic edifices is inhibited until the lithosphere cools and thickens sufficiently to support them [17]. The low T_m values for Nefertiti and 29°N 49°E suggest that Bell Regio has atypically thin lithosphere for a highland region on Venus. Alternatively, magmatic activity in Bell Regio may have been restricted in time to an era of high heat flux.

Several factors can alter the interpretations of the admittance data. Subsurface loading of the plate by buoyant material will decrease the observed admittance. Such loading is observed on Earth as underplating of cumulate material, intermediate in density between crust and mantle, at the base of the crust beneath large volcanoes [18, 19]. If the observed admittance in such an area is interpreted using a surface loading model, estimates of T_e are biased to erroneously low values. If underplating is a significant process at volcanoes on Venus, the estimated T_e values may be lower bounds. On the other hand, dynamic topography and gravity effects from mantle convection may result in high admittance values that mimic or overprint a purely flexural signal [20]. If there is significant power at the wavelengths analyzed, the dynamic contribution will bias T_e to erroneously high values. These complications can be minimized by calculating the coherence between gravity and topography, which is relatively insensitive to the mode of loading (surface or subsurface) [21].

Conclusions. Gravity/topography admittances have been used to estimate elastic plate thicknesses and infer thermal gradients and heat flux beneath several large volcanoes on Venus. The resulting heat flow values are lower (by a factor of 2 or more) than those expected if global heat loss scales from that on Earth. Thus, steady-state thermal models, though marginally permitted, are not favored. On the other hand, the estimated thermal boundary layer thickness of 100 to 150 km is a factor of two less than that predicted by current episodic convection models [14, 22]. New models for the thermal evolution of Venus are thus called for.

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