IMPLICATIONS OF STRESS MODELING FOR VOLCANIC STRUCTURE AND MAGMATIC FLUX ON VENUS; Patrick J. McGovern[1] and Sean C. Solomon[2]; [1]Dept. of Earth, Atmospheric, and Planetary Sciences, M. I. T., Cambridge, MA 02139; [2]Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015.

Summary. We describe a new structural model for large volcanoes on Venus emphasizing the importance of material that fills the flexural depression beneath the edifice. The moat-filling material is integral to the structure of volcanoes on Venus, in contrast to the fragmented and structurally weak character of material that fills flexural moats around volcanoes on Earth. Neglect of this moat-filling material will cause underestimation of volcanic flux by an order of magnitude. Models of resurfacing and thermal evolution of Venus must be able to accommodate a significant magmatic flux during the period of large volcano construction that was comparable to the current terrestrial intraplate eruption rate.

Moat structure and volcanic flux. On the basis of finite element modeling of stresses and displacements induced by flexural loading of the lithosphere by a large volcanic edifice [1], we have suggested that volcanoes on Venus develop with a welded basal boundary condition. Such a condition inhibits catastrophic failure of the flanks, a prominent feature of terrestrial hotspot volcanoes [2, 3], but not generally seen for large volcanoes on Venus. Flexurally-induced topographic moats surrounding large terrestrial volcanoes are partially [4] to completely [5] filled by the products of catastrophic flank failure and erosion of the edifice. Moat-filling material is therefore a significant fraction of the output of terrestrial hotspots [5]. On Venus, topographic moats surrounding large edifices are not generally evident (only three have been documented [1]). Instead, radially oriented flows appear to fill completely the flexural depression [1]. Large edifices on Venus often exhibit radial lineations, fractures, and graben, which are interpreted to be the surface manifestation of dikes intruded from a central magma chamber [6]. These inferred dikes are often observed to extend through the flow apron and even beyond. Such dikes could not propagate through the fragmented material that fills terrestrial moats and are therefore evidence for the solid nature of the moat fill.

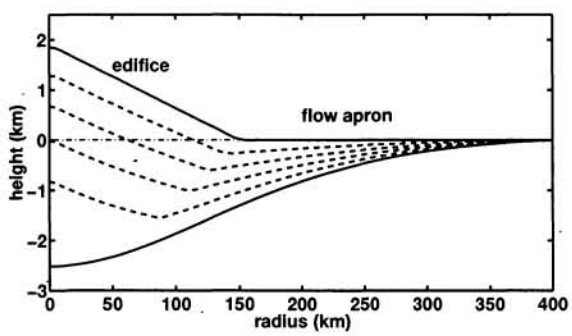

Figure 1: Synthetic volcano stratigraphy.

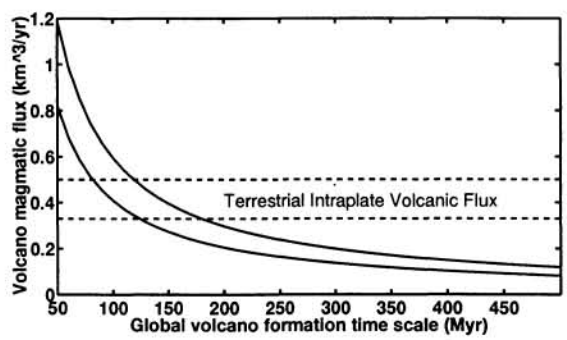

Figure 2: Volcano magmatic flux.

Common assumptions about volcano structure tend to yield erroneously low volumes (and thus low estimates of volcanic flux). Typically, workers determine edifice heights and radii and use a conical approximation to determine volcano volumes (e.g., [7]), ignoring the volume of moat-filling material beneath and around the edifice. Such values are then used to estimate a flux integrated over all the volcanoes of Venus [8], which then forms a basis for discussions of resurfacing rates (e.g., [9]). To help visualize and quantify the importance of moat-filling flows, we construct a synthetic stratigraphic cross section of a volcano on Venus by superposing the results of several plate flexure calculations (Fig. 1). We use an axisymmetric thick-plate flexure solution [10], and we assume that the moats are filled to the pre-existing surface level by flows of final density equal to that of the central edifice. To account for this infill, we set the buoyant restoring force proportional to the density contrast between volcanic material and mantle. We perform the calculation for a progression of edifice sizes that represent equal-volume conical loading increments on a lithosphere with elastic thickness $T_e = 35$ km. In Fig. 1, the upper solid line represents the final topography of the edifice and moat fill; the lower solid line is the deflection of the top of the lithosphere, and dashed lines denote surfaces at intermediate growth stages. Note that the volume of the edifice is only a small fraction f_e (14% for the model in Fig. 1) of the total volume of erupted material. This fraction not a strong function of volcano size or elastic plate thickness; however, it depends on the density contrast at the crust-mantle boundary (500 kg/m^3 in this model). Reducing this contrast to 300 kg/m^3 reduces f_e to about 10%.

We estimate the volcano magmatic flux on Venus as follows. For each of 145 large volcanoes we measured a "topographic radius" R_t, defined by a break in slope at the edifice edge. Height is then measured from the summit to the elevation of the slope break. Approximating the edifice as a cone ($V = \pi R_t^2 h/3$), the total

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volume of edifices $V_{te} = 6.0 \times 10^6$ km^3. The total volume of material erupted at large volcanoes (V_{tv}) is then V_{te}/f_e. For the values of density contrast described above, this ratio is in the range 7–10. Thus, $V_{tv} = 4$–6×10^7 km^3. Given V_{tv} and an assumed duration τ_v for the period during which large volcanoes formed on Venus, the volcano magmatic flux is $\dot{m}_v = V_{tv}/\tau_v$. This quantity is shown in Fig. 2 vs. τ_v for V_{te} equal to 4 and 6 $\times 10^7$ km^3. For comparison, bounds on the present terrestrial intraplate magmatic flux $\dot{m}_t$ (the sum of oceanic intraplate and intracontinental volcanic rates [11]) are also shown.

We have suggested [1] that volcano construction on Venus occurred after the postulated global resurfacing event, once the lithosphere had become sufficiently thick to support large volcanic loads. If so, the age of the resurfacing event t_{gr} provides an upper bound on τ_v and thus a lower bound on $\dot{m}_v$. Estimates of t_{gr} range from 300 to 500 Ma [9, 12]. Under the assumption that the long-term eruption rate at large volcanoes has been approximately constant since that time, we set $\tau_v = t_{gr}$. This assumption yields magmatic flux estimates of 0.1 to 0.2 km^3/yr, about a quarter to half of the current intraplate volcanic flux $\dot{m}_t$ on Earth [11]. Evidence from stratigraphy [13] and crater counts [14, 15] indicates that large volcanoes are significantly younger than the global mean surface age. While a crater retention age for large volcanoes of 0.5 t_{gr} [14] is consistent with $\tau_v = t_{gr}$, a younger crater age [15] would favor a lesser value of τ_v. With $\tau_v = 150$ Myr, for instance, the implied volcano magmatic flux (Fig. 2) is 0.3 to 0.4 km^3/yr, comparable to $\dot{m}_t$. The quantity $\dot{m}_v$ is a lower bound on the overall planetary magma supply rate $\dot{m}_p$ because it ignores contributions from other volcanic features such as shield fields, small- and intermediate-sized shields [8], extensive flow fields [16], rift-related volcanism, and recently active coronae, as well as intrusive emplacement of intermediate-density material within or at the base of the crust (underplating), as observed at terrestrial hotspot volcanoes [5, 17]. Rift and corona volcanism may increase $\dot{m}_v$ by a factor of 2; intrusion may increase it by a factor of 2–10 [18]. However, any intruded or underplated material that compensates the volcanic load would reduce the required amount of moat fill, and can be considered to be accounted for in the above calculation.

Venus resurfacing. This proposed structure for Venus volcanoes has important implications for scenarios of global resurfacing and the estimation of planetary volcanic fluxes. From the spatial distribution of impact craters and the paucity of deformed and externally embayed craters, *Strom et al.* [9] have argued for a global resurfacing event of short ($\approx$ 10 Ma) duration, followed by a 300 to 500 Ma period of low rates of volcanism (0.01–0.15 km^3/yr). These volcanic flux estimates are well below the estimated terrestrial intraplate flux [11], as well as our best estimates of $\dot{m}_p$. The rates cited in [9], however, are based on the assumption that resurfacing occurs by the emplacment of thin (< 1 km) flow units. Moats for typical-sized Venus volcanoes will be several kilometers deep, violating this assumption. Moat filling limits the areal extent of flows, while accommodating a significant flux of magma (and interior heat) to the surface. Moat filling increases the ratio of volume to surface area for the volcanism that occured after the global resurfacing event and provides a mechanism for reconciling the observed decrease in areal resurfacing rates after plains emplacement [15] with the existence of a steady, significant magma flux to the surface.

Venus thermal history. Our estimates of magma flux provide a new constraint on the thermal evolution of Venus. The planet must have been able to produce at least 4–6 $\times 10^7$ km^3 of magma sometime after the global resurfacing event. In one class of models for the global resurfacing event [19], a period of widespread lithospheric recycling and high magmatic and thermal flux is followed by an extended period of lithospheric stability, low magmatic flux, and low heat flow, and a present thermal lithosphere thickness of 300 km or more. The amount of melt produced by a plume increases with increasing plume potential temperature and decreasing lithosphere thickness [20]. Models in which a very thick lithosphere underlies recently active large volcanoes on Venus may require unrealistically high plume potential temperatures. Such thick lithospheres, however, are not required by the current set of geophysical observations [21]. If lithospheric thicknesses and plume potential temperatures are similar on Venus and Earth, similar magmatic fluxes imply similar plume-delivered heat fluxes.

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