FLEXURAL STRESSES AND MAGMA ASCENT AT LARGE VOLCANOES ON VENUS. P. J. McGovern, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058, USA (mcgovern@lpi.usra.edu).

Introduction: The Magellan mission to Venus [1] revealed the presence of at least 144 large volcanic edifices (i.e., those with flows extending > 100 km in diameter; Figure 1) [2-4]. Numerical models of coupled edifice growth and lithospheric flexure on Venus [5] revealed that horizontal compression in the upper lithosphere gets transmitted into the edifice, tending to halt magma ascent (and thereby, edifice growth) in the absence of mitigating circumstances such as thick elastic lithosphere or buoyant subsurface loading (mantle dynamic or crustal underplating). Here I examine in detail the ways in which lithospheric flexural stresses influence magma ascent at Venustian volcanoes. In particular, I present two forms of magma-stalling “stress traps” and discuss how they may affect the growth of several types of volcano on Venus.

Data: Large volcanoes on Venus are typically shallowly sloped (generally < 5 degrees) domes or cones covered by numerous radially oriented lava flows that extend outward to a nearly flat flow apron, as seen at Sapos Mons and Irimi Mons (Figure 1). Sapos Mons exhibits very narrow annular zones of extensional faulting on the eastern and western mid-flanks [6]. Radial fractures extend from the lower flanks and flow apron, preferentially to the north-northeast, southeast and southwest directions. Sapos Mons thus qualifies as a radiating fracture system [7]. Irimi Mons (Fig. 1) exhibits the radial flows typical of large volcanoes, but also has a prominent tectonic annulus surrounding an annular ridge [3, 8]. The tectonic annulus and ridge qualify this feature for inclusion in a database of coronae [e.g. 9], a class of volcano-tectonic feature defined by topographic and/or tectonic annuli. However, the topography of the lower flanks of Irimi Mons and the radial flows in the distal flow apron [e.g., 4] suggest that this construct is representative of a hybrid class of structures transitional between volcanoes and coronae [10,8,5].

Models: Finite element models of the interaction between edifice growth and lithospheric flexure at large volcanoes on Venus showed that flexurally induced horizontal compression in the upper lithosphere was transmitted into the growing edifice [5]. Given that dikes tend to form perpendicular to the least compressive principal stress [11], the modeled stress states in the upper lithosphere and edifice predicted lateral magma emplacement in sills rather than vertical ascent in dikes (as predicted for the lower lithosphere). The horizontal compressive stresses thus form a “stress trap” for magma, preventing ascent and thereby inhibiting edifice growth. However, several factors mitigate this stress trap [5]: the magnitude of horizontal compression decreases with increasing elastic lithosphere thickness $T_L$, and horizontal compression is relieved by uplift from underplating, dynamic support, or intrusion.

Recent advances in modeling techniques [12] allow the introduction of intrusions as displacements enforced between adjacent rows of finite elements. Sill-induced uplift further alters the lithospheric stress state by relieving horizontal compression in material above the sill [12] possibly re-opening magma ascent paths to the surface. Further, sill intrusion can generate mid-flank slope breaks and annular or radial fault systems at the surface of the volcano, as observed at Alba Patera on Mars [12] and Irimi Mons on Venus (Fig. 1). These results suggest the importance of subsurface buoyant and intrusive loading at volcanoes like Irimi Mons.

Despite recent progress, there are still further conditions to consider for models of magma ascent through the lithosphere. The three sources of pressure available to drive magma flow in vertical dikes (Eqn. 7 of [13], modified to account for our “extension positive, z positive upward” sign conventions): 

\[
(dP/dz + \rho_m g) = -\Delta \rho g + d\Delta \sigma / dz + d\Delta P / dz \quad (\text{Eqn. 1}.
\]

where $P$ is magma pressure, $\rho_m$ is magma density, $\Delta \rho$ is the local excess magma pressure, and $\Delta \sigma$ is the differential stress, defined as the difference of horizontal normal stress and vertical normal stress ($\sigma_x - \sigma_z$; this is termed the “tectonic” stress by [13]). The left-hand term in the above equation is a factor in the relation for mean magma flow velocity $u_z$ given laminar flow (Eqn. 4 of [13]):

\[
u_z = \frac{1}{3} \eta w^2 (dP/dz + \rho_m g) \quad (\text{Eqn. 2}).
\]

where $\eta$ is the magma viscosity and $w$ is the dike half-thickness. For $z$ defined positive upward (note: this choice makes $g$ negative), the quantity $dP/dz + \rho_m g$ must be positive to obtain magma ascent (flow in the positive $z$ direction). In the absence of other pressure sources (right side of Eqn. 1), magma ascent requires that the differential stress gradient $d\Delta \sigma / dz$ be positive, i.e., that differential compression increases with height (otherwise, by Eqn. 2, magma would be forced downward rather than upward.) Thus, even though principal stress orientations in the lower lithosphere are consistent with vertical dikes, the upward increase in horizontal compression will in effect “squeeze off” the dikes, preventing magma ascent beyond the top of the ductile zone (Fig. 2). In practice, magma overpressure ($d\Delta P / dz$) and buoyancy forces
(Δρg) may at least partially compensate for a negative differential stress gradient (Eqn. 1).

The pressure terms in Eqn. 1 lead to a new criterion for stress-trapping of magma in the lithosphere. The differential stress gradient term dΔσ_y/dz can reach very high magnitude in flexed lithosphere, dominating the right hand term of equation 1. Preliminary Tekton finite element models of stresses resulting from volcanic loading on Venus (Fig. 2) demonstrate the importance of differential stress gradients. Differential stresses peak in two horizontal layers: at the intersection of the upper lithosphere and lower edifice (in horizontal principal compression) and at the top of the lower lithospheric ductile zone (horizontal principal extension). The differential stress gradient is greatest between these two layers, in the “elastic core” of the lithosphere. By a purely Andersonian (stress orientation) ascent criterion [e.g., 12], magma ascent should be favored wherever Δσ is positive. The region between the lithosphere midplane (at depth z around 4-8 km, where Δσ = 0; see Fig. 2) and the top of the ductile region satisfies the stress orientation ascent criterion (e.g., vertical dikes are predicted), but fails the stress gradient criterion (the magma in such dikes would tend to be squeezed downward). The need to satisfy two criteria for magma ascent therefore places even greater constraints on scenarios for growth of large volcanic constructs than was previously appreciated [e.g., 12]. Nonetheless, mitigating factors can help to create conditions favorable for magma ascent. For example, the magnitude of differential stress gradients in the lithosphere decreases with increasing T, (Fig. 2). Density contrast Δρ and local overpressure ΔP can offset high negative Δσ. The buoyancy contribution is enhanced if a large fraction of the mechanical lithosphere consists of high-density mantle material. Buoyant uplift from crustal underplating can relieve horizontal compression in the upper lithosphere. Finally, Fig. 2 demonstrates that sill emplacement shifts the zero-crossings of differential stresses and stress gradients upward (compare black triangles to black circles), facilitating magma ascent through the lithosphere above the sill (above d = 12 km in Fig. 2). Such a scenario may account for the tectonics and structure of Irmini Mons (Fig. 1).