MAGMA RESERVOIR RUPTURE BENEATH A VENUSIAN EDIFICE: WHEN DOES LITHOSPHERIC FLEXURE BECOME SIGNIFICANT? B. S. Murphy[1], K. S. Metcalfe[1], G. Ruiz[1], L. G. Curtin[1], S. R. Chestler[1], J. C. Penido[2], J. K. Muller[1] and E. B. Grosfils[1]; [1]Geology Department, Pomona College, CA 91711 (egrosfils@pomona.edu); [2]Department of Astronomy, Mount Holyoke College, MA 01075.

Introduction: Many factors affect the location at which a pressurizing magma reservoir ruptures, including the depth and shape of the magma chamber, the presence of mechanical layering, edifice loading, etc. [e.g., 1-5]. Recently, numerical models incorporating a large conical edifice have been used to demonstrate that flexure of the lithosphere modifies reservoir rupture characteristics significantly [6]; however, these models only utilized a single large edifice geometry, two elastic thicknesses, and a fixed spherical reservoir volume. Here, via a parameterized analysis that incorporates (a) different edifice geometries and volumes, (b) variable reservoir aspect ratios and volumes, and (c) a range of elastic thicknesses, we strive to add depth and breadth to our understanding of the role played by flexure. Specifically, through comparison with an edifice-loaded configuration in which no flexure occurs [3], our goal is to identify when the induced flexural stress state within the lithosphere alters the reservoir's rupture characteristics (i.e. location at which tensile failure occurs, orientation of the fracture) and, as a result, the style of intrusion and magma transport from the reservoir that takes place.

Methods: Following [2] and [6], a static, axisymmetric FEM analysis of a pressurized ellipsoidal cavity, isolated from edge effects in a uniform elastic host subjected to lithostatic loading, was performed using COMSOL Multiphysics (www.comsol.com). The lithosphere of elastic thickness T_e is treated as a disk 900 km in radius, with a Winkler restoring force applied to the base (using an asthenosphere density of 3300 kg m^{-3}) and roller conditions employed along the outer margin. Fluid stresses applied normal to the interior reservoir wall incorporate (a) a uniform magma pressure P, which counteracts the lithostatic load in the host rock to keep the reservoir open and also includes any excess pressure, and (b) a magma weight term $P_m = \rho_m gh$, where h is the depth below the crest of the reservoir with magma of density ρ_m. For all models Poisson's ratio is 0.25, Young's Modulus is 100 GPa, and for simplicity magma and host rock density are set to a single value (2800 kg m^{-3}) while the tensile strength is assumed to reflect the presence of pervasive pre-existing fractures (~0 MPa). Key geometric parameters examined are summarized in Table 1.

Elastic Thickness	20 – 70 km
Volcano Height	0.625, 2.5, 5 km
Volcano Radius	54.5, 100, 200 km
Reservoir Aspect Ratio	0.3 – 1.2
Reserv. Depth (Center)	3 – 65 km

Table 1: Model parameter ranges explored.

Results: In the absence of flexure, a spherical reservoir beneath an edifice fails at the crest until it is extremely close to the free (pre-edifice) surface [3]. Figure 1 shows a summary of the results for a spherical reservoir with a radius of 1 km when a flexural displacement is included. Blue areas in the plots show combinations of T_e and reservoir depth for which no measureable change in rupture location is caused, i.e. failure continues to remain locked at the crest just as in the non-flexural case. In contrast, both red and green areas indicate combinations of T_e and reservoir depth that shift rupture to the base (red) or middle (green) of the reservoir, i.e. identifying conditions for which the stresses introduced by lithospheric flexure play a pivotal role by altering where the reservoir wall will fail. For all models, as in similar non-flexural studies [2-4], failure creates fractures perpendicular to the rz-plane, favoring the formation of vertical (radial) dikes at or near the crest, sills near the midsection, and circumferential intrusions in between.

Beneath a large edifice (Figure 1A), flexure does not alter rupture location (blue region) when the elastic thickness is very large (exceeding ~50 km) and the reservoir is located at great depths (exceeding ~20 km). At smaller elastic thicknesses or for shallower reservoirs, rupture is shifted to the base (red region) or midsection (green region) of the reservoir. Elastic thickness estimates for Venus typically fall in the 20-30 km range but vary considerably, from 0-100 km

[7-9]; unless T_e is unusually large and the reservoir is exceptionally deep, flexure is expected to redirect the flow of magma downward, thereby terminating upward migration and the potential for further edifice growth. At smaller edifice sizes (Figures 1B and 1C) a decrease in the magnitude of the flexural response means that reservoir failure at the crest is increasingly likely (blue regions), thereby promoting continued edifice growth though lateral redirection into sills (green regions) remains plausible for reservoirs forming at the shallowest depths.

Implications for Edifice Evolution: Spherical reservoirs beneath volcanoes <1 km tall and only a few tens of kilometers in radius will continue to rupture at the crest and feed magma toward the surface unless the reservoirs formed at very shallow depth (Figure 1C). Continued edifice growth is thus expected unless magma availability becomes a limiting factor. As an edifice grows, however, enhanced flexural response acts to shut down the transport of magma to the surface unless the edifice is located in an area exhibiting an unusually large (for Venus) elastic thickness. Even in such a circumstance, however, the reservoir must reside at considerable depth to avoid failure leading to lateral sill injection. Ultimately, as edifice height and radius grow the flexural load increasingly prohibits continued growth through centralized upward migration of magma in all but the most exceptional circumstances; the general conditions shown in Figure 1A represent a plausible upper limit for volcano size on Venus unless elastic thickness exceeds ~50 km, in agreement with the maximum observed height of 5.5 km [10]. Conceptually this is not a surprise [11-13] but, even for the simple circumstance presented here as an example (spherical reservoir), models that integrate reservoir inflation with lithospheric flexure are yielding significant new quantitative insight into the conditions under which edifice growth becomes self-limiting. Complementary insight into the relative importance of reservoir geometry will also be presented.

References: [1] Parfitt *et al.,* 1993, *JVGR,* 55, 1-14. [2] Grosfils, 2007, *JVGR*, *166*, 47-75. [3] Hurwitz *et al*., 2009, *JVGR*, *188*, 379-94. [4] Long and Grosfils, 2009, *JVGR*, *186*, 349-60. [5] Manconi *et al*., 2007, *GJI, 170*, 952-958. [6] Galgana *et al*., 2011, *JGR*. *116,* 1-12. [7] Barnett *et al.*, 2000, *Icarus, 146*, 404-419. [8] Hoogenboom *et al.*, 2005, *JGR, 110,* E09003 [9] Anderson and Smrekar, 2006, *JGR, 111*, E08006. [10] Keddie and Head, 1994, *P&SS, 42*, 455-462. [11] McGovern and Solomon, 1993, *JGR, 98,* 23553-23579. [12] McGovern and Solomon, 1998, *JGR, 103*, 11071-11101. [13] McGovern and Rumpf, 2007, *LPSC,* abst. 2387.

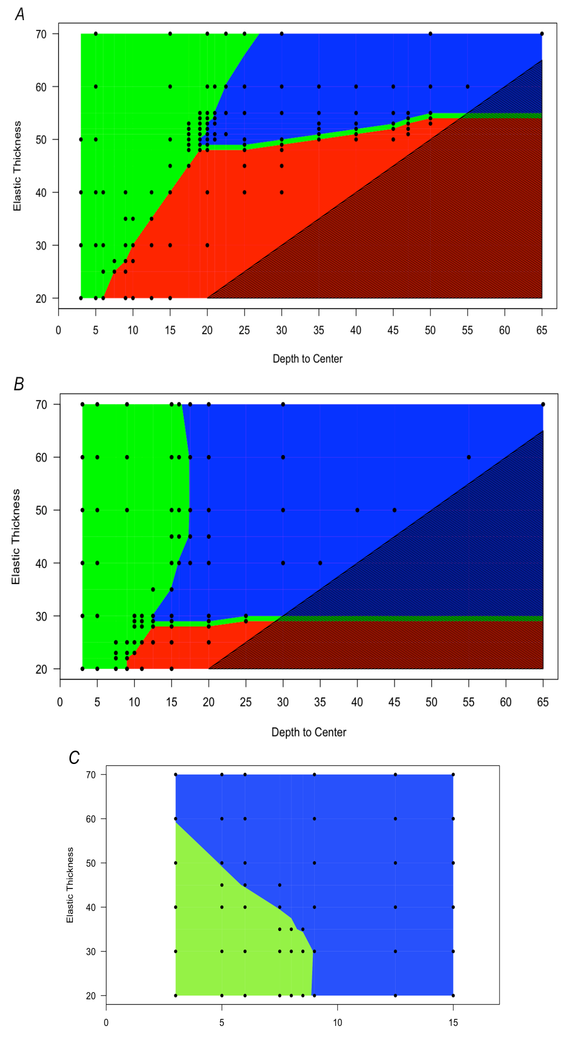

Figure 1. Contours of rupture location as a function of T_e and reservoir depth for a spherical reservoir of radius 1 km; black dots identify model runs, and thin green strip between red and blue areas is a contouring artifact. Red: failure at reservoir base. Blue: failure at reservoir crest. Green: failure occurs a few tens of degrees from the reservoir mid-depth. Conical edifice heights and radii are [A] 5 km height, 200 km radius, [B] 2.5 km, 100 km and [C] 0.625 km, 54.5 km. Dark shading indicates T_e < reservoir depth (implausible); x-axis scale in Figure 1C is different than in 1A&B.