RADIAL DIKE FORMATION ON VENUS FROM UPPER LITHOSPHERE MAGMA CHAMBERS: INSIGHTS FROM MODELS OF UPLIFT, FLEXURE AND MAGMATISM.

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Introduction: Giant radial lineament systems, thought to form through lateral emplacement of dikes at shallow depth [e.g., 1-2], are among the most intriguing volcano-tectonic structures on Venus. Initial reconnaissance mapping at C1-MIDR resolution [1] revealed ~120 such features, with average radii of ~325 km although some examples extend more than 2,000 km; however, active global mapping efforts using higher resolution FMIDR images are revealing ~5-fold more examples [e.g., 3].

While the presence of radiating dike systems on Venus (plus Earth and Mars) is well established, and a link to shallow magma chambers is compelling in many instances [e.g., 2], we have only limited insight into the conditions that promote the formation of laterally extensive radial dike systems. For example, simple models of chamber pressurization predict propagation of radial dikes directly from the reservoir [e.g., 4-6]; however, such models fail to account for the full effects of gravitational loading, and it has been shown that models accounting for the fully loaded stress tensor predict different patterns of intrusion [e.g.,7]. Similarly, while the stress state beneath an edifice can provide conditions in which dikes ascending vertically from a ruptured chamber transition to lateral radial propagation at shallow depth [8], this effect is limited by the edifice size, and to date no model with appropriate boundary conditions has demonstrated circumstances that promote the growth of regional-scale dike swarms such as those observed on Venus. Here, to begin remedying this shortcoming, we explore whether the interplay between lithospheric flexure and magma chamber pressurization can create stress conditions favoring emplacement of giant, laterally propagating, shallow radial dike systems.

Models: Within our axisymmetric numerical finite element models the gravitationally loaded lithosphere is assumed to have a basaltic composition, represented at two different thicknesses (i.e., T_e = 20, 40 km), initially without and later with spherical magma chambers embedded at different depths. Horizontal movement is constrained at the distal part of the model, while Winkler buoyant forces are imposed at the base. We use a lithosphere model with an uplift scenario (uplift load equivalent to a 5 km-thick, 200 km-radius conical load times the lithosphere-asthenosphere density contrast of 500 kg/m^3, applied at the model center) to represent the initial stages of radial dike formation, but also run models that combine uplift with edifice loading to better simulate periods of active volcanism.

We use the orientation of principal extensional (σ_E) and compressive (σ_C) stresses, as well as differential stress (σ_D) magnitudes, as key indicators denoting whether radial dike, sill or cone sheet formation is favored. Stresses in the lithosphere are locally perturbed through dynamic processes inflating a 1 km radius magma chamber placed at various depths. Following [7], we impose overpressures along the reservoir wall until it reaches the onset of the extensional stress regime and thus tensile failure.

Results: Models of buoyant subsurface loading produce a flexural stress state with high σ_D in the upper and lower parts of the lithosphere, separated by a σ_D minimum in the neutral plane (Fig. 1). The principal stress patterns at depth show $\sigma_E = \sigma_\theta$ (out of plane) and, $\sigma_C = \sigma_V$ (vertical) throughout the upper lithosphere, predicting the formation of radial graben in the upper lithosphere, either by brittle failure (faulting) or as the surface expression of radially intruding dikes. In the lower lithosphere, $\sigma_C = \sigma_H$, (horizontal) and $\sigma_E = \sigma_V$, with sills as the predicted intrusive form. Magma reservoirs emplaced in the upper lithosphere and at the neutral plane (blue and green curves in Fig. 2, respectively) are predicted to fail at the crest (where tangential stress $\sigma_T = \sigma_\theta$), while those emplaced in the lower lithosphere (red curves in Fig. 2) tend to fail near the midsection, predicting horizontal intrusions (since $\sigma_T > \sigma_\theta$). Magma reservoirs in the neutral plane region require significantly larger overpressures to induce failure, compared to those embedded in the upper and lower lithosphere (Fig. 2).

Discussion: Our models, though preliminary, have important implications for the formation of radial dike swarms from magma chamber pressurization. In the upper half of an uplifted lithosphere, a pressurized chamber fails at the crest, and predicted intrusion orientations are radial (Figure 2). Thus, initial magma transport from the top of an upper lithosphere chamber will occur via vertically propagating, radially-oriented dikes, a result similar to those derived from recent half-space models [7] except that superposition of flexure also produces a pervasive extensional environment in the upper lithosphere (with $\sigma_E = \sigma_\theta$, Fig. 1). Such a stress gradient greatly facilitates magma ascent in dikes [9-12]; given an appropriate magma source at depth, i.e.

one commensurate with the flexural uplift imposed, voluminous outpourings of magma at the surface would be predicted. How does this promote the growth of lateral radial dikes? The situation is similar to that at rift zones in Hawaii, where laterally propagating dikes must be "trapped" by increasing compression at both the upper and lower tips of the dike [13-14]. A natural lower trap is the compressional stress state in the lower lithosphere (Fig. 1). The upper trap, if not initially present, occurs once an edifice or similar surface load is created during the initial outpourings of magma onto the surface. Hurwitz et al. [8] found that compression beneath an edifice in the absence of flexure could cause a dike to "roll over" to a lateral mode of propagation. This effect will be amplified when a flexural response is allowed, because the induced compression will generally be of much larger magnitude [e.g., 15] than the elastic subsidence stresses beneath small edifices [8]. The presence of compressive stresses, and hence the likelihood that ascending radial dikes can transition into a lateral propagation mode, depends on the relative timing/magnitude of upward (subsurface) vs. downward (surface edifice) loading. This is, however, a self-correcting system: in the absence of an edifice, stress conditions favor eruptions and surface loading. Any edifice constructed will not feel the extensional stresses created during previous uplift [e.g., 15], and can therefore provide the compression necessary to halt continued vertical propagation of the upper dike tip. If fracturing remains possible at the lateral edges of the dike, a geologically plausible occurrence [14], then shallow radial dikes that propagate significant lateral distances become possible.

Since the detailed behavior of intrusive pathways at any given time may depend sensitively upon a “see-saw” balance between upward and downward loading processes, it becomes possible to combine our model results with the topography and volcanic stratigraphy observed at the surface and use these data together to place firmer constraints on the temporal evolution of individual magmatic centers on Venus. This effort is ongoing. To illustrate the potential value of the results, however, consider a circumstance in which volcanism sufficient to form an edifice has occurred: the relative timing of uplift, intrusion, and eruption then determines whether or not a strong surface lineament system (dike swarm) is evident at the present day. In uplifts associated with low magma production, the surface volcanism may be a thin veneer covering the structure, leaving a strong surface expression of diking/faulting. In uplifts with high magma production, the volcanism may have been so voluminous as to cover almost all surface expressions of the dike swarms. Thus, the varied states of dike swarms may contain clues to magmatic production and the thermal state of the lithosphere, a topic we are continuing to explore.

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Figures

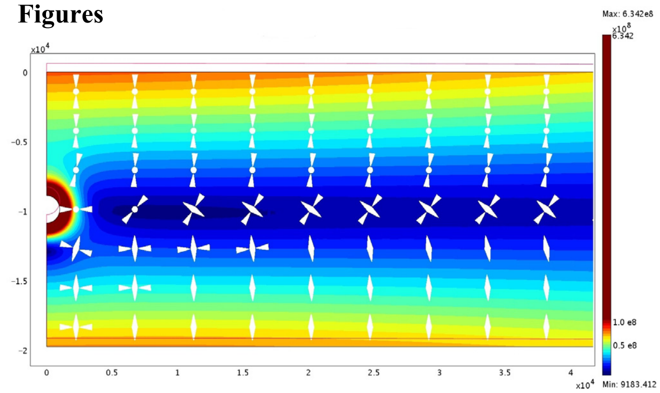

Figure 1. Cross-section of axisymmetric model with uplift (Depth to reservoir center *DtC* = 10 km, T_e = 20 km; *x,y* axes in meters). Colors correspond to differential stresses (red = high, blue = low, units = Pa). Arrows = principal stress axes (Arrows pointing inwards = compression; arrows pointing outwards=extension; dots=out-of-plane). Red outline shows deformed lithosphere.

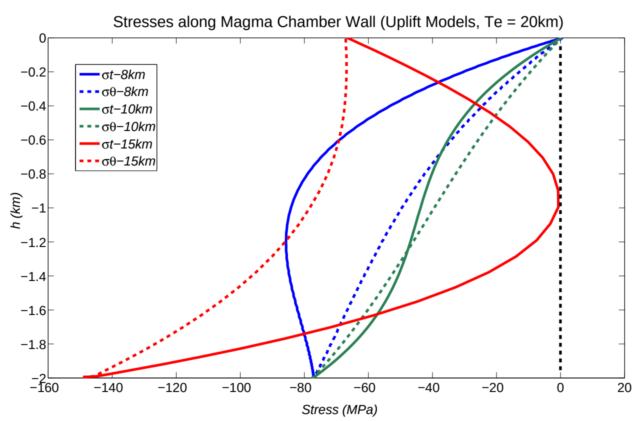

Figure 2. Tangential (σ_t, dashed lines) and circumferential (σ_θ, solid lines) stresses along magma chamber wall, for models with *DtC*s = 8 (blue), 10 (green), and 15 km (red), T_e = 20 km. Failure (dashed black line = failure line, at $\sigma = 0$) occurs at the crest for reservoirs situated at the upper lithosphere and neutral plane, and failure near the midsection for reservoirs situated at the lower lithosphere.