MAGMA ASCENT PATHWAYS ASSOCIATED WITH LARGE MOUNTAINS ON IO. P. J. McGovern[1], M.R. Kirchoff[2], O.L. White[3], and P.M. Schenk[1], [1]Lunar and Planetary Institute, USRA, 3600 Bay Area Blvd., Houston, TX 77058 (mcgovern@lpi.usra.edu), [2]Southwest Research Institute, 1050 Walnut St., Suite 300, Boulder CO 80302 (kirchoff@boulder.swri.edu), [3]NASA Ames Research Center, Moffett Field, CA, 94035-1000 (oliver.l.white@nasa.gov).

Introduction: While Jupiter's moon Io is the most volcanically active body in the solar system, the largest mountains seen on Io are created by tectonic forces rather than volcanic construction [1-3]. Pervasive compression, brought about by subsidence induced by sustained volcanic resurfacing and aided by thermal stress [4], creates the mountains, but at the same time inhibits magma ascent in vertical conduits (dikes) [5]. However, the superposition of stress states from crustal resurfacing/recycling and mountain loading can result in viable pathways of magma ascent through nearly the entire lithosphere. The viability of these pathways appears to be strongly related to the thickness of the mechanical lithosphere on Io, which is thought to correspond closely to the thickness of Io's crust (pervasive melt generation in Io's upper mantle limits the strength of any mantle contribution to the lithosphere). We superpose stress solutions for subsidence and thermal stress (from resurfacing) in Io's lithosphere with stresses from Io mountain-sized loads (in a shallow spherical shell solution) in order to evaluate magma ascent pathways. We use stress orientation (least compressive stress horizontal) and stress gradient (compression decreasing upwards) criteria to identify ascent pathways through the lithosphere.

Models and Methods: We calculate stresses from mountain loading on Io using a shallow spherical shell formulation [6], as described in [7] and using the correction of [8]. This formulation accounts for both flexural and membrane responses to loading. We calculate two components of horizontal normal stress, the radial stress and the out-of-plane, or "hoop" stress. The main parameter controlling the response to loading is the thickness of the elastic lithosphere T_e.

We calculate stresses in Io's lithosphere that result from crustal recycling [4], accounting for thermal, Poisson, and subsidence stresses as a function of depth in the crust. There is one important difference: we assume laterally unconstrained material, i.e., a post-faulting stress state presuming stress release on existing faults [see also 9]. In practice, the difference amounts to a rightward shift of the curves in ref. [4] such that the upper lithosphere is in extension. We focus on the linear rheology models (power-law exponent $n = 1$) to allow mathematically legal superposition with the lithospheric loading models described above. The parameter β that sets the strength of subsidence stress relative to thermal stress in the model is initially assigned a value of 0.2 [4].

We employ two stress-based magma ascent criteria to assess potential magmatic pathways through Io's crust/lithosphere. The first ascent criterion simply states Anderson's [5] finding that intrusions tend to form perpendicular to the least compressive principal stress. A second, less well-known ascent criterion is based on pressure balance in vertical dikes [10]. In practice, when flexure is significant (see below) the vertical gradient of tectonic stress (difference between horizontal and vertical normal stress) dominates the pressure balance. In general, this term must be positive for magma ascent, i.e., differential compression must decrease with height; otherwise, magma would be forced downward rather than upward.

We assume that magma will not ascend in a given location unless both of the criteria outlined above are satisfied. Failing to satisfy the stress orientation criterion will tend to result in lateral rather than vertical magma transport, in sills rather than dikes. Failing to satisfy the stress gradient criterion will result in "squeezing off" of potential dikes due to increased compression in their upper regions [10]. We term regions where both criteria are satisfied "Ascent-favorable zones" or "AFZs".

Results and Discussion: Mountain loading stresses, for locations beneath the mountain (Fig. 1, blue line), tend to decrease (get more compressive) with increasing height in the lithosphere, while crustal recycling stresses (Fig 1, green line) show an opposite trend. The superposition of these two types of stress can nearly cancel out at some radial distance from the mountain center, leaving a stress curve with slightly positive (extensional) stress and stress gradients throughout all but the lowermost lithosphere (Fig. 1, dashed line). Such a curve satisfies both magma ascent criteria throughout almost the entire thickness of the lithosphere. Such locations form the vertical part of a "U"-shaped AFZ (Fig. 2) facilitating magma transport from near the bottom of the lithosphere (under the center of the mountain) to its surface (beneath the flank of the mountain).

"U"-shaped AFZs generally appear for mountain loads greater than 100 km in radius and 10 km in (pre-loading) height, dimensions comparable to those observed at a significant number of mountains on Io [e.g., 11]. Reducing the β parameter to 0.1 allows creation of "U"-shaped AFZs at somewhat smaller dimensions and increases the radial distance of the vertical part of the "U". "U"-shaped AFZs do not form for values of T_e substantially greater than or less than 50 km. In the former case the thicker lithosphere reduces the magnitudes of the mountain-loading stresses below the levels at which they can balance out the crustal recycling stresses (see Fig. 1). In the latter case near-vertical stress superposition curves like those in Fig. 1 occur at higher values of extensional stress, such that much of the curve exceeds the Byerlee [12] criterion for brittle failure (Fig. 1, black diagonal lines): when faulting would reset the stresses to fall on the Byerlee criterion, the negative slope of that curve would violate the stress gradient magma ascent criterion (in contrast, the superposed stress curve in Fig. 1 remains under the Byerlee criterion).

The "U"-shaped pathways appear to be the most robust, as they provide for magma transport from very deep in the lithosphere to its surface, albeit beneath some fraction of the mountain topography. Nonetheless, models with "U"-shaped AFZs are consistent with the presence of volcanic sources (e.g., paterae) incised into or on the margins of Io's mountains, resembling, for example, Tohil Mons. Magma may reach the surface by thermally eroding the mountain flanks from below, perhaps accounting for the apparent incision of Radegast Patera into Tohil Mons, and/or by ascending through fractures that extend through the mountain and surrounding terrain, as observed at the volcanic center Pillan [13]. Further, magma may be able to exploit the thrust faults that built the mountains as magma conduits to reach the surface at the margins of the mountains, consistent with observations of volcanic eruption in compressional environments like the Andes Mountains on Earth and analogue mechanical models of coupled thrust faulting and magmatic ascent [14].

The extreme compression at the base of the lithosphere (Fig. 1) is the reason why no AFZ in Fig. 2 reaches the bottom of the lithosphere. Thus, this compression is the remaining major barrier to magma ascent. Re-melting of the lower crust/lithosphere (the bottom of the "conveyor belt" cycle), enhanced by the increased heating the mountain "root" will experience as it subsides into the partially or completely molten [15] upper mantle, would remove this last barrier.

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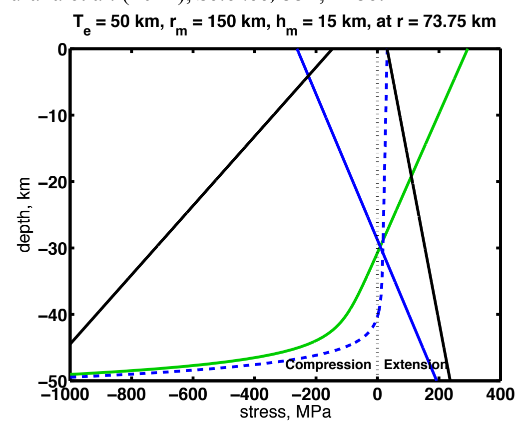

Figure 1. Superposition (dashed blue curve) of crustal recycling stress (green curve) with mountain loading stress (blue curve). T_e = 50 km, mountain radius r_m = 150 km, mountain height (pre-loading) h_m = 15 km, at radial distance from mountain center r = 73.5 km. Byerlee [12] failure criteria (black diagonal lines) are shown in compression and extension.

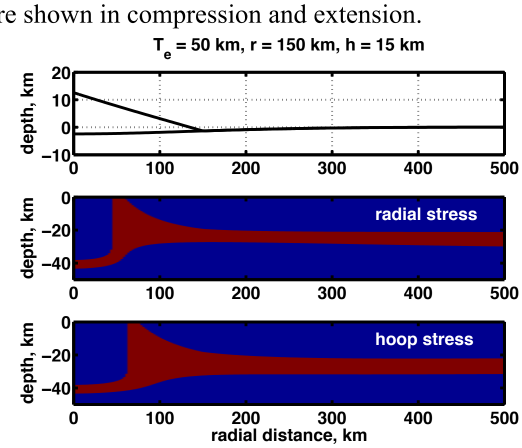

Figure 2. Post-loading topography (top panel) and magma ascent criteria satisfaction vs. r for superposed models of crustal recycling and mountain loading stresses (bottom panels), for T_e = 50 km, h_m = 15 km, and r_m = 150 km. Red areas denote where both stress orientation and tectonic stress gradient ascent criteria are satisfied, blue areas denote where one or more criteria are not satisfied.