MAGMA ASCENT AT LUNAR IMPACT BASINS: EFFECTS OF LITHOSPHERIC TECTONIC STRESS GRADIENTS, BRITTLE FAILURE, AND VOLATILE GENERATION. P. J. McGovern[1], W. S. Kiefer[1], G. Y. Kramer[1], M. T. Zuber[2], J. C. Andrews-Hanna[3] and J. W. Head III[4]. [1]Lunar and Planetary Institute, USRA, 3600 Bay Area Blvd., Houston, TX 77058 (mcgovern@lpi.usra.edu), [2]Dept. EAPS, M.I.T., Cambridge, MA 02139, [3]Dept. of Geophysics, Colorado School of Mines, Golden, CO 80401, [4]Dept. of Geological Sciences, Brown University, Providence, RI 02912.

Introduction: Large impact basins on the lunar nearside are filled with basaltic lava flows: the lunar maria. Lava flow emplacement requires ascent of the basaltic magma from the mantle source region, through the crust, to the surface. Melt buoyancy, defined as $\Delta\rho|g| = (\rho_{rock} - \rho_{melt})|g|$, where ρ is density and g is planetary gravity, is a key driver of magma ascent in many terrestrial and planetary settings [1, 2]. Basaltic melt buoyancy is strongly negative (adverse to magma ascent) in the lunar crust due to the low density of crustal material, as revealed by data from the Gravity Recovery and Interior Laboratory (GRAIL) mission [3]. The ascent-promoting effects of lithospheric tectonic stress gradients [4], induced by flexural support of loads related to super-isostatic lunar basin mass concentrations (mascons) [5] and sub-isostatic crustal annuli around basins [6], have been invoked as a means of creating zones of enhanced magma ascent in the vicinity of such loads. However, the adverse buoyancy of basaltic melts in crust is still large enough to present problems to such scenarios. Further, the intersection of loading stress profiles with the "Byerlee" bounding envelope for frictional sliding on faults [7] will tend to create adverse tectonic stress gradients in the uppermost lithosphere. An additional positive contribution to magma ascent comes from overpressure via gas generation [8], such as generation of carbon monoxide (CO) gas as determined from analysis of Apollo 17 orange glass [9].

Here we reconsider the driving forces for magma ascent in dikes, merging the stress gradient calculations [5, 6] with the more traditional approach of balancing the positive buoyancy of melts in the mantle with the negative buoyancy in the crust [e.g., 1, 2, 10], to determine the minimum depth in mantle from which melts can ascend and how this depth is affected by loading stresses in the lithosphere, brittle failure, and volatile generation.

Methods: We use an analytic loading solution [11-13] that includes both flexural and membrane support to calculate deflections and stresses of an elastic lithosphere from super- and sub-isostatic loads. The loading stresses are used to predict locations of favored magma ascent based on two criteria: stress orientations at the top and bottom of the lithosphere (horizontal extension [14]) and stress gradients throughout the lithosphere (extension increasing upwards, [4]). For flexural loading alone, one of these criteria is violated somewhere in the lithosphere [5]. However, for small planets like the Moon, membrane stresses can place segments of the lithosphere into extension with positive stress gradients [5, 6], allowing direct ascent of magmas from the mantle to the surface. We make the simplifying assumption that the elastic lithosphere (T_e) and crustal (T_c) thicknesses are the same.

We calculate magma ascent velocity u_z in a dike of width w [4]:

$$u_z = (1/3\ \eta)\ w^2\ (d\Delta\sigma_y/dz + d\Delta P/dz - \Delta\rho\ g) \qquad (1)$$

where η is magma viscosity, $\Delta\sigma_y$ is the tectonic stress (tension positive), or horizontal stress σ_y minus vertical stress σ_z, $d\Delta\sigma_y/dz$ is the vertical gradient in tectonic stress, $d\Delta P/dz$ is the gradient in overpressure, and $-\Delta\rho\ g$ is magma buoyancy (g is negative in our coordinate system so positive buoyancy increases u_z). We calculate an "effective buoyant density" [4, 6] by equating the first and third terms in the rightmost parentheses and solving for $\Delta\rho_{efb}$. For the elastic core of the lithosphere, the stress-related contribution to buoyancy $\Delta\rho_{efbec}$ is calculated using $d\Delta\sigma_y/dz$ from the loading model. For the part of the lithosphere where stresses exceed the Byerlee criterion (brittle failure), the contribution to buoyancy $\Delta\rho_{efbbf}$ has a value close to -2000 kg/m^3. For overpressure contributions, we calculate an effective buoyant density as follows. Since the initial generation depth is where volatile pressure first exceeds lithostatic, with ascent to some higher level the volatile pressure will exceed lithostatic by the difference in lithostatic pressures at the two levels: thus, the effective buoyant density for gas generation $\Delta\rho_{efbga}$ is simply ρ_{crust}.

Following [1, 2, 10] we evaluate the pressure in a standing column of magma that spans the thickness $T_m + (T_c - T_b) + T_b$ where T_c is the crustal thickness, T_m is the minimum depth below the base of the crust of the melt source region, and T_b is the thickness of the brittle failure region (atop the crust/lithosphere). and equate it to the lithostatic pressure within a column of the same dimensions, yielding the following equation for T_m

$$T_m = (\Delta\rho_2(T_c - T_b) + \Delta\rho_3\ T_b)/(-\Delta\rho_1) \qquad (2)$$

where $\Delta\rho_1 = \rho_{mantle} - \rho_{melt}$, $\Delta\rho_2 = \rho_{crust} - \rho_{melt} + \Delta\rho_{efbec}$, and $\Delta\rho_3 = \rho_{crust} - \rho_{melt} + \Delta\rho_{efbbf}$. T_m corresponds to the minimum base level of a dike in which magma could

reach the surface. For the case with a generation depth T_x (less than T_b) we add a layer and eqn. (2) becomes

$$T_m = (\Delta\rho_2(T_c - T_b) + \Delta\rho_3 (T_b - T_x) + \Delta\rho_4 T_x)/(-\Delta\rho_1) \quad (3)$$

where $\Delta\rho_4 = \rho_{crust} - \rho_{melt} + \Delta\rho_{efbga}$.

Results: For a model load corresponding to the Serenitatis basin with T_e and T_c = 40 km (Fig. 1), the adverse stress gradient induced by brittle failure keeps T_m (red line) at a deep level in the mantle, significantly below the level at which it would be in a stressless lithosphere (red dotted line, calculated without the $\Delta\rho_{efb}$ terms). However, when volatile generation is added (green line), T_m shows a marked minimum at about 470 km radius, demonstrating that magma ascent is enhanced vs. the stressless case over a broad region. For a thinner lithsophere ($T_e = T_c$ = 30 km), T_m reaches the base of the crust near r = 410 km, minimizing the vertical extent of dikes required to allow ascent to the surface. For a thicker lithosphere ($T_e = T_c$ = 50 km), the proximity of T_m to the base of the crust is reduced, as is the elevation of the T_m curve over that for the stressless case. For larger loads such as Imbrium (Fig. 2), increased stress gradients allow T_m to intersect the crustal base at higher T_e values than for Serenitatis.

Discussion: The calculations of Figs. 1-2 demonstrate that the combined effects of lithospheric stress gradients and volatile generation can enhance magma ascent and eruption around large loads on the Moon. In the case of Serenitatis basin, stresses from the initial basin-filling loading raise the level of the interface T_m in an annular zone around the basin, corresponding to the relative location of the Tranquillitatis basalts [5], that include high-density titanium-rich magmas.

In the absence of overpressure from volatile generation, lithospheric stresses are likely to be a main driver of magma ascent [5, 6], subject to dike arrest at the depth of the brittle failure envelope. We also calculated an effective T_m for ascent to the level of brittle failure (T_b, blue curves) in the absence of overpressure, shown as the red dashed curves in Figs. 1 and 2. These curves are very similar to those that include overpressure (green lines), again demonstrating loading-enhanced magma ascent in relatively shorter dikes than for the stressless case. When the dikes encounter the failure envelope at depth -T_b, lateral rather than vertical propagation of basin-radial dikes is favored, with this depth becoming an effective level of neutral buoyancy of the dikes. A radial dike scenario may account for the Serenitatis-radial Rimae Cauchy in Tranquillitatis.

Ease of magma ascent increases with decreasing lithospheric and crustal thickness, the former by increased stress gradients in the elastic core of the lithosphere and the latter because the region of adverse density contrast (the crust itself) is thinner [1, 2]. The trend with lithosphere thickness suggests an optimum thermal state for stress-enhanced magma ascent, with T_e comparable to T_c and not significantly larger.

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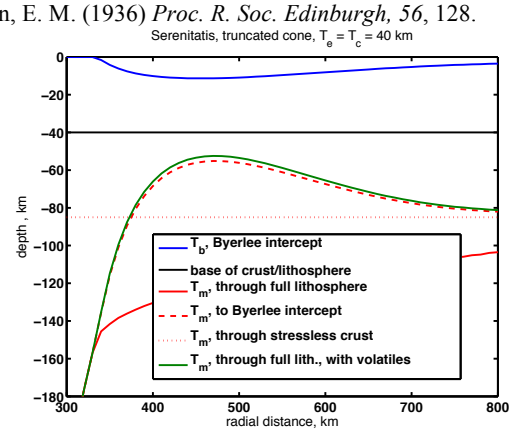

Figure 1. Vertical locations of interfaces T_m and T_b vs. radius from center of load, for a Serenitatis-sized load [5, 13], $T_e = T_c$ = 40 km, calculated using the horizontal out-of-plane (or "hoop") normal stress. Black curve: base of lithosphere. Red solid curve: ascent through full stressed lithosphere. Red dashed curve: ascent to T_b. Red dotted curve: ascent through stressless lithosphere. Green curve: ascent with volatile generation.

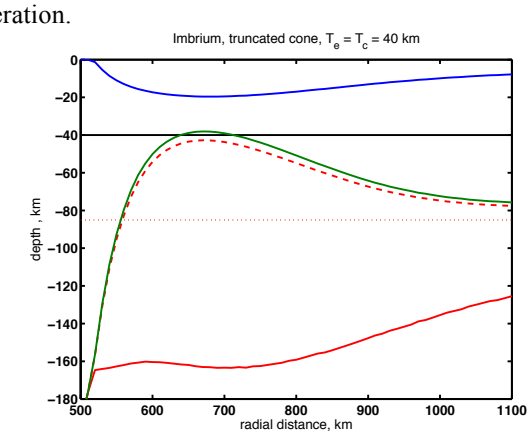

Figure 2. As in Figure 1, for Imbrium basin.