

LOADING STRESSES AND MAGMA ASCENT IN AND AROUND LARGE LUNAR IMPACT BASINS: SCENARIOS FOR THE EMPLACEMENT OF MARE BASALTS.

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Introduction: The broad expanses of mare plains on the Moon are primary manifestation of the volcanic and thermal evolution of that body. In particular, enormous volumes of mare basalt fill most of the largest basins on the lunar nearside. Here, we show that the filling of such basins creates a mechanical response beyond their rims that greatly facilitates magma ascent, and discuss the implications for the evolution of various Maria.

Methods: We use an analytic loading solution [1] that includes both flexural and membrane support to calculate deflections and stresses of an elastic lithosphere from basin-filling mare loads [e.g., 2-4]. 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 [5]) and stress gradients throughout the lithosphere (extension increasing upwards, [6]). For flexural loading alone, generally one of these criteria is violated somewhere in the lithosphere, requiring mitigating contributions such as magma overpressure or buoyancy [4, 7]. However, for small planets like the Moon, the effects of membrane stresses (constant through the thickness of the lithosphere) can place segments of the lithosphere into extension with positive stress gradients, eliminating the need for mitigation [e.g., 4].

We use lithospheric stress gradients to calculate magma ascent rates. The equation for ascent velocity in a dike of width w is [6, combining several equations]:

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

where η is magma viscosity, $d\Delta\sigma_y/dz$ is the stress gradient, also called the vertical gradient in tectonic stress (or VGTS), $d\Delta P/dz$ is the gradient in overpressure, and $-\Delta\rho g$ is magma buoyancy (g is negative in our coordinate system so buoyancy increases u_z). We adopt values of $w = 10$ m and $\eta = 100$ Pa/s.

Results: We show model results (Fig. 1, 2) for a load with shape and magnitude comparable to that inferred for Serenitatis [3]. The thickness of the elastic lithosphere T_e is 50 km, also an appropriate value for the early history of basins like Serenitatis, based on analysis of inversion of fault populations [2,3]. The radial and tangential normal stress curves (Fig. 1) show the combined effects of flexure, with stress gradients

between bottom and top of lithosphere, and membrane support, raising both tangential stresses into extension beyond the load. We focus on this region, where extensional tangential stress predicts basin-radial orientations of intrusions and faulting. At no location in the model domain are all ascent criteria satisfied by the radial stresses. However, the tangential stresses satisfy those criteria in an annular zone beyond the load.

Calculated ascent velocities (Fig. 2) demonstrate that this annulus is a strongly favored zone of magma ascent. Even for an adverse density contrast of -150 kg/m³, magma would still be able to ascend near the middle of this zone. Figure 2 demonstrates the importance of the VGTS gradient in the force balance for dikes [6]. Positive VGTS (extension increasing upward) creates an "effective buoyancy" that counteracts the negative buoyancy of dense basaltic melts. Note that Fig. 2 does not account for stress mitigating factors that make ascent even more likely [e.g., 4,7]. For melts with favorable buoyancy and overpressure conditions, ascent would be even faster and more broadly distributed than shown in Fig. 2, although the most vigorous volcanism would be centered on the identified ascent zone.

Discussion. A successful model for ascent of mare basalt magmas must account for the observation that they are denser than the anorthositic crust. Arguments based on hydraulic head and neutral buoyancy theory have been invoked [e.g., 8], but others argue that evidence from geophysical studies (e.g., crustal thickness models) render such explanations unlikely [9]. These workers calculated basaltic melt densities from sample compositions and found that some are less dense than the upper crust, although the majority are more dense. They invoked removal of the upper crust to explain ascent of mare magmas, although exotic thermal conditions (superliquidus temperatures) were required to account for emplacement of high-density basalts in Procellarum [9], and basalts emplaced on elevated, thicker-crust regions, e.g., East Tranquilitatis and Insularum (south of Imbrium) present difficulties.

Our calculations show that ascent of high-density basaltic magmas is a natural outcome of the stress state induced by initial basin loading and infill by mare basalts. Such an initial stage might be facilitated by the initial thermal perturbation from impact and the fractured state of the crust above the mantle melt zone, as

well as by removal of low-density upper crust [9]. Once initial basin-filling loads are established, subsidence generates the stress state with favorable absolute magnitudes (horizontal extension) and gradients (extension increasing with height) throughout the elastic core of the lithosphere, in an annular zone surrounding the load.

The superposition of loading stresses from several basins may greatly enhance prospects for magma ascent. Along an axis between basin centers, loading stresses will constructively add, potentially doubling the effect seen in Fig. 2. For example, Mare Tranquilitatis lies between the basins Serentatis on one end and Nectaris and Fecunditatis on the other. Thus, the Tranquilitatis magmas may have been assisted by the favorable loading stress state. This scenario in particular resolves difficulties with emplacing basalts at the high elevations of east Tranquilitatis. Mare Tranquilitatis flows have been dated as several hundred million years older than the flows currently covering Serenitatis [10], suggesting that interior loading at Serenitatis was established at a correspondingly early time. A similar spatial relationship holds for Imbrium on one side and Humor and Nubium on the other, with elevated mare (Insularum) between them.

Imbrium, being the largest nearside basin [11], should have a very broad favored zone of ascent, and therefore may have enhanced the volcanic evolution of a large fraction of the Moon's surface. In addition to Insularum, much of Mare Procellarum falls within this zone, and the stress-enhanced ascent velocities here help to solve problems with the inferred high density of Procellarum basalt melts [9]. The growth of volcanic provinces such as the Aristarchus Plateau and Marius Hills [e.g., 12] may also be facilitated by the favored ascent zone. The "eyebrow" shape of Mare Frigoris may result from magmas exploiting the proximal reaches of Imbrium's favored zone, filling the depression between successive rings of Imbrium [e.g., 11]. Paradoxically, the favored ascent zone may not exist around the largest basins, (e.g., South Pole-Aitken) because the flexural (stress gradient-inducing) component of support is much weaker relative to the membrane component. This may contribute to the relative paucity of magmatism associated with SP-A.

If the mechanism proposed here has operated around lunar basins, there should be evidence for tectonic and structural features oriented radial to basin centers. The Imbrium "radial sculpture", including the Alpine Valley [11] may be such a signature. Also, the Imbrium-radial orientation of some of the youngest mare units [10, 13] is suggestive of this sort of control.

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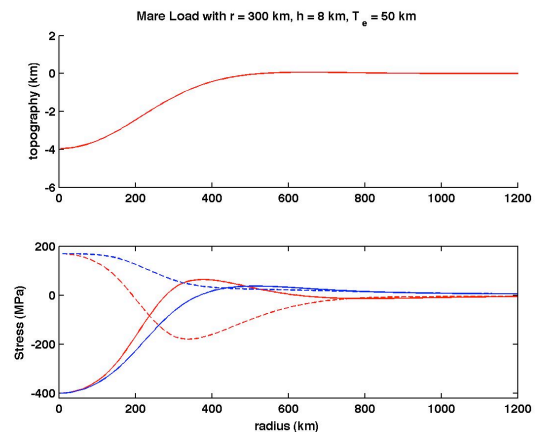


Figure 1: Lithospheric deflection (**not** basin topography) and stress generated by truncated cone-shaped model load of radius $r = 300$ km and height $h = 8$ km. $T_e = 50$ km. Stress plot: Blue curves are tangential stress, red curves radial stress, solid curves top of lithosphere, dashed curves bottom of lithosphere.

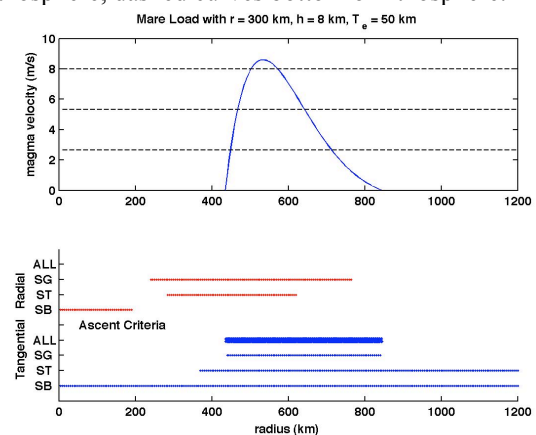


Figure 2: Magma ascent criteria (bottom) and ascent velocity (top) as functions of radius from center of model load. SB and ST indicate extensional stress at bottom and top of lithosphere, SG indicates positive stress gradient, and ALL is the intersection of the three. Dashed lines in top plot indicate effects of $\Delta\rho = 50, 100,$ and 150 kg/m^3 .