THE RELATIONSHIP BETWEEN THE HEIGHT OF A VOLCANO AND THE DEPTH TO ITS MAGMA SOURCE ZONE: SOME POPULAR MISCONCEPTIONS; Lionel Wilson[1,2], Elisabeth A. Parfitt[2] and James W. Head[2] [1] Environmental Science Division, Institute of Environmental and Biological Sciences, Lancaster University, Lancaster LA1 4YQ, U.K. [2] Geological Sciences Department, Brown University, Providence RI 02912, U.S.A.

Basic concepts.

It is commonly assumed that the maximum height above the regional geoid level to which a volcanic edifice is able to grow can be related to the depth of formation of the partial melts which provide its magma supply. This relationship has been used to infer aspects of the thermal and stress state of the lithosphere beneath volcanic constructs on Earth [1, 2, 3], Mars [4], Io [5] and Venus [6].

The essential assumptions underlying such a model are that (i) a continuous pressure connection exists within the volcanic edifice between the melt source zone and the vent; (ii) the pressure in the country rocks surrounding the melt source is the local hydrostatic pressure dictated by the depth below the geoid (with no load contribution by the edifice itself); and (iii) the melt has a net positive buoyancy relative to the rocks through which it rises. Let the depth from the geoid to the top of the melt source zone be H_s (measured positive downwards) and the height of the summit of the volcano above the geoid be H_v (measured positive upwards); the densities of the volcanic edifice rocks, the melt, and the lithosphere in the vicinity of the volcano, averaged over the vertical distances to which they apply, are ρ_v, ρ_m and ρ_l, respectively (see Fig. 1); g is the acceleration due to gravity. Then on balancing the pressures due to the weights of the magma and the country rocks at the partial melting level:

$$\rho_l\, g\, H_s = \rho_m\, g\, (H_s + H_v) \quad .... \ (1), \quad \text{and thus} \quad H_s = H_v\,[\rho_m/(\rho_l - \rho_m)] \quad .... \ (2).$$

When the melt is on average positively buoyant relative to the lithosphere through which it rises (the commonest case), $(\rho_l - \rho_m)$ is positive and so H_v is also positive. However, in the case of basalts attempting to rise through the anorthositic lunar lithosphere, $(\rho_l - \rho_m)$ was commonly negative [7]; this implies that H_v must also be negative, which is why eruptions could only take place into, and could only partly fill, the mare basins [8].

Discussion.

It is easy to show that each of the three assumptions underlying the above treatment is flawed:

(i) The evidence from terrestrial volcanoes such as Kilauea is that discrete batches of magma ascend from the mantle to accumulate in a magma reservoir under the summit of the volcano. These batches move through a region which offers less resistance (both viscous and elastic) than elsewhere since it has by definition been pre-heated by earlier magma batches [9-11]. Each batch proceeds as an isolated dike opening a new fracture ahead of it, the fracture nearly closing again behind the batch [12], but leaving a thin ribbon of melt behind which then cools to the ambient (sub-solidus) temperature. There is little possibility of a continuous fluid column extending from the source region to the reservoir or to the surface (though a connection from reservoir to surface may exist during summit eruptions). Even if several successive batches of melt follow the same path from the source region, so that a new batch rises along the hot ribbon left by the previous batch, the ribbon will commonly have cooled sufficiently that the magma in it exhibits non-Newtonian rheology; a finite yield strength will then be involved in transmitting stresses along the ribbon. Also, even if, in extremely rare circumstances, a continuous, hot liquid column did extend from the source zone to the surface via the reservoir, it is still the case that the pressure difference measured through the liquid would not be equal to the hydrostatic pressure in the country rocks adjacent to the source zone, for it is well established that the stresses required to allow a dike to propagate necessarily involve an excess pressure being present inside the dike, relative to the lithostatic load [13, 14].

(ii) It is difficult to make a case for completely neglecting the local load imposed on the magma source zone by the volcanic edifice. If this load is included, (1) becomes:

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$\rho_l\, g\, H_s + \rho_v\, g\, H_v = \rho_m\, g\, (H_s + H_v)$ .... (3), and so $H_s = H_v\, [(\rho_m - \rho_v)/(\rho_l - \rho_m)]$ .... (4).

Now, although $(\rho_l - \rho_m)$ can still plausibly be assumed to be positive, $(\rho_m - \rho_v)$ is likely to be negative, since much of the volcanic edifice consists of the solid, cooled (and hence denser) form of its own melt (but see further comments below); this implies that no positive volcano can form in the first place! Clearly, the problem can be avoided by assuming that the extra load imposed by the edifice is shared by a finite region at the depth of the source zone, so that only some fraction α of the term $\rho_v\, g\, H_v$ is involved. Equation (4) then becomes

$H_s = H_v\, [(\rho_m - \alpha\, \rho_v)/(\rho_l - \rho_m)]$ .... (5), and H_v can be positive if $\alpha < \rho_m/\rho_v$ .... (6),

where ρ_m/ρ_v, at least for terrestrial basalts, is likely to be of order 0·92. The value which should typically be assumed for α must be based on an assessment of the distribution of crustal stresses in the vicinity of the volcano; that these stresses are not simply hydrostatic, however, ensures the violation of the second of the above assumptions.

(iii) The net buoyancy of the magma between its source and the surface is by no means assured. Indeed, the presence of shallow magma chambers and shallow volcanic rift zones, such as those possessed by Hawaiian volcanoes on Earth and by many of the Tharsis volcanoes on Mars, is direct evidence for the trapping of rising magma at neutral buoyancy zones [14, 15]. These zones exist because magma in general contains volatiles; the volatiles exsolve as a magma approaches the surface, either producing vesicular lava flows (from which gas can escape during flowage, or to which vesicles can be added by the late-stage exsolution of volatiles), or leading to explosive eruptions of vesicular ash and scoria. The result is that the surface rocks of a volcano are not simply the solid form of the melts which rise from depth - or even the exactly equivalent solid versions of the vesicular magmas nearing the surface. The eruption products accumulate in a stochastic fashion, and the tendency is for the surface and near-surface rocks to be significantly more vesicular than the rising magma. Compaction under gravity (which occurs on all planets) and hydrothermal alteration (which is probably confined to Earth and perhaps some parts of Mars) cause an increase of bulk density with depth, and neutral buoyancy of the rising magma occurs at a depth of order 2-3 km (on Earth) [16]. It is this density distribution, *combined with the fact that melts rise in isolated batches*, that allows magma reservoirs to form in terrestrial volcanoes. If magma ascended from the partial melt zone along a dike extending *continuously* to the surface, the negative buoyancy of the magma near the surface might well be offset by the positive buoyancy over the rest of the travel distance, allowing the magma to erupt. The fact that shallow magma reservoirs are common serves to underline, therefore, not only the lack of net buoyancy of the magma but also the lack of a continuous pressure connection between the magma source zone and the surface. We conclude that any relationship which may exist between volcano height and depth of magma source must be *much* more complex than that which is currently commonly assumed.

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