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FACTORS CONTROLLING THE STRUCTURES OF MAGMA CHAMBERS IN BASALTIC VOLCANOES.

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Magma chamber depths The depth to the center of a magma chamber is most probably determined by the density structure of the lithosphere. A chamber forms where the density of melts ascending from partial melting zones at depth is equal to the density of the surrounding crustal rocks: the melts are trapped at a neutral buoyancy level [1, 2]. The density of ascending melts decreases slowly as they rise at first due to decompression; eventually, at depths shallow enough that gas exsolution begins, a much more rapid decrease occurs. The density of the country rocks increases with depth due to the compaction of vesicles and pore spaces, filling of vesicles and pore spaces by hydrothermal alteration products, and ultimately by mineral phase changes.

For a given surface rock density, the depth to reach a given compaction state is probably pressure dependant, and so scales as g^{-1}: magma chamber centers would be ~2.65 times deeper on Mars than Earth (i.e. ~10 to 15 km), and about 15% shallower on Venus than Earth, if this were the only factor. If the surface rock density is less on Mars than Earth (lower atmospheric surface pressure leading to greater rock vesicularity in volcanic areas), the depths to chamber centers would be even deeper on Mars (by a factor closer to 1 than 2). If surface rock densities are higher on Venus than Earth (the high surface pressure essentially eliminating vesicularity [3]), the depths to chamber centers could be much shallower on Venus than Earth.

Presumably hydrothermal alteration is absent on Venus; however, the chemical consequences of migration of carbon dioxide-rich fluids needs to be assessed. The temperature and water availability controls on hydrothermal alteration processes on Mars are also not easy to assess, but are more likely to be depth-dependent than pressure-dependent, thus acting in opposition to the pressure-related reduced compaction trend.

Vertical extents of magma chambers It is commonly assumed that magma chambers grow until the stress on the roof, floor and side-wall boundaries exceeds the strength (compressive or tensile, as appropriate) of the wall rocks. Attempts to grow further lead to dike propagation events which reduce the stresses below the critical values for rock failure. If a magma chamber center lies at a depth D below the surface in country rocks of density ρ_{cu}, the local pressure is $P_L = \rho_{cu}\, g\, D$, where g is the gravity. If the pressure at the magma chamber center is P_c, then the excess pressure acting across the side-wall is $P_0 = P_c - P_L$. At a vertical height h above the chamber center the pressure inside the chamber is $P_{iu} = P_c - \rho_m\, g\, h$ and outside the chamber is $P_{eu} = P_L - \rho_{cu}\, g\, h$, where ρ_m is the magma density. The stress across the wall is then $(P_{iu} - P_{eu}) = (P_c - P_L) - g\, h\, (\rho_m - \rho_{cu}) = P_0 - g\, h\, (\rho_m - \rho_{cu})$. Typically $(\rho_m - \rho_{cu}) \sim 300\ kg/m^3$.

Table 1 shows values of $(P_{iu} - P_{eu})$ for P_0 in the range 1 to 9 MPa and a series of values of h; equivalent values of h for the Earth, Mars and Venus are given. On the assumption that the tensile strength of the country rocks is 4 MPa and the compressive strength is 7 MPa, the Table indicates by (T) and (C) the combinations of P_0 and h which lead to tensile or compressive failure of the walls. The tensile failure conditions near h = 0 lead to lateral dike intrusion events. Compressive failure at large values of h leads to cracks in the roof and possibly slight subsidence of roof blocks. Any magma intruded into these cracks freezes and re-seals the roof; any massive subsidence of blocks extending all the way to the surface represents a caldera collapse event, but also leads to loading of the magma in the chamber by the weight of the overlying blocks. The consequent increase in $P_0 = P_c - P_L$ then causes lateral, rather than vertical, dike propagation. These arguments suggest that vertical magma chamber extents will be ~ 2·65 times greater on Mars than Earth (the ratio of the gravities).

Failure of the magma chamber roof in compression does not lead to upward magma migration since $\rho_m > \rho_{cu}$; summit eruptions are most likely triggered by magma vesiculation in the upper part of the chamber where ambient pressures are lowest. Table 2 shows the consequences of introducing a "foam" layer Δh thick which contains 50% by volume gas at the top of a magma chamber. It is clearly possible to produce tensile failure of the roof as long as a sufficiently thick layer of foam can be generated.

Lateral extents of magma chambers The later growth of magma chambers is accomplished by lateral dike injection into the country rocks. The patterns of growth and cooling of such dikes are controlled in a complex way by a combination of the current value of P_0, the regional stress gradients, and the previous history of activity of the chamber [1, 4, 5]. Much further work is required in this area, but ultimately the lateral extent of a chamber must represent a balance between two episodic (and probably stochastic)processes: recharge from the mantle and discharge to form intrusions or eruptions to the surface.

References: [1] Rubin, A.M. & Pollard, D.D. (1987) Ch. 53 , U.S.G.S. Prof. Paper 1350. [2] Walker, G.P.L. (1988) Ch. 41, U.S.G.S. Prof. Paper 1350. [3] Head, J.W. & Wilson, L. (1986) J.G.R. 91, 9407-66. [4] Parfitt, E.A. & Wilson, L. LPSC XIX, 903-4. [5] Parfitt, E.A., this vol.

Table 1. Values of the interior excess pressure ($P_{iu} - P_{eu}$) in a magma chamber as a function of the height, h, above the center line and the center-line excess pressure P_0. Failure conditions are indicated by the letters T (tensile) and C (compressive).

h(Earth)	h(Venus)	h(Mars)	P_0 = 1	3	5	7	9 MPa
0	0	0	1.00	3.00	5.00T	7.00T	9.00T
1000	1114	2649	-1.94	0.06	2.06	4.06T	6.06T
2000	2227	5297	-4.88	-2.88	-0.88	1.12	3.12
3000	3341	7946	-7.82C	-5.82	-3.82	-1.82	0.18
4000	4455	10595	-10.76C	-8.76C	-6.76	-4.76	-2.76

Table 2. Values of the interior excess pressure in a magma chamber as a function of the height, h, above the center line and the thickness, Δh, of a foam layer at the top of the chamber, for a center-line excess pressure of P_0 = 5 MPa. To use the table, read down the column for Δh = 0 as far as the height proposed and then replace the entry for that height with the entry on the same line in the column for the value of Δh proposed.

h(Earth)	h(Venus)	h(Mars)	Δh = 0	100	300	500	700	900 m
0	0	0	5.00:T	6.27:T	8.82:T	11.37:T	13.92:T	16.47:T
1000	1114	2649	2.06	3.33	5.88:T	8.43:T	10.98:T	13.53:T
2000	2227	5297	-0.88	0.39	2.94	5.49:T	8.04:T	10.59:T
3000	3341	7946	-3.82	-2.55	0.00	2.55	5.10:T	7.65:T
4000	4455	10595	-6.76	-5.49	-2.94	-0.39	2.16	4.71