

NEUTRAL BUOYANCY ZONES IN THE VENUS LITHOSPHERE: INFLUENCE ON VOLCANIC LANDFORMS AND THE PRESENCE OR ABSENCE OF MAGMA CHAMBERS; L. Wilson^{1,2} & J.W. Head¹. ¹ Geological Sciences Department, Brown University, Providence, RI 02912, U.S.A.; ² Environmental Science Division, Lancaster University, Lancaster LA1 4YQ, U.K.

Introduction A volatile-bearing magma passes through 2 critical pressure levels/depths as it rises to a planetary surface. At the first, the nucleation level, the magma is just saturated in the volatile. If atmospheric pressure is less than the nucleation pressure, volatile bubbles exsolve somewhere below the surface. At the second critical level expanding bubbles occupy ~75% of the total magma volume and it disrupts, the spray of released gas and entrained pyroclasts erupting explosively [1]. Atmospheric pressure on Venus is so high that the second critical condition will not be reached, even at the surface [2], unless total magma volatile contents are ~2 - 4 wt%, depending on vent elevation relative to the mean planetary radius. Thus, steady, basaltic fire-fountain eruptions are unlikely to occur. But for basaltic Venus magmas with similar volatile contents to those on Earth, the first critical condition will commonly be met, and surface lavas will be vesicular. Vesiculation is the main control on bulk density in near-surface volcanic country rocks. Density variation with depth is due to compaction of progressively buried surface layers and pore space infilling by secondary minerals. Similar bulk density increases with depth are found for Hawai'i and Iceland [3, 4] from seismic wave speed data and, at depths of a few km, the densities of typical basaltic melts are close to those of the country rocks [5]. Magma batches rising as isolated diapirs or dikes, disconnected from their source zones, become trapped at such neutral buoyancy levels to evolve into magma reservoirs. Dikes leaving over-pressured magma chambers will not grow to the surface unless country rock elastic properties are very non-uniform or gas exsolution makes the magma buoyant [6,7]. The commonest result of dike production is thus lateral chamber growth. A large magma volume loss can cause chamber underpressuring and failure of the overlying country rocks, subsidence of which forms a fault-bounded caldera (or regional depression). Thus, the presence or absence of a shallow magma chamber is a major indicator of the depth variation of density of country rocks relative to that of the magma, and is a major factor in determining the morphological evolution of the edifice.

Analysis We model the increase of country rock density, ρ_c , with depth in a volcanic region as being due to progressive compaction by the weight of overlying material; the fractional void space, $V(P)$, then decreases exponentially with increasing pressure, P , so that if λ is a constant:

$$V = V_0 \exp(-\lambda P) \quad (1), \quad \rho_c(V) = \rho_\infty(1-V) \quad (2), \quad \text{and} \quad \rho_{\text{surf}} = \rho_\infty(1-V_0) \quad (3),$$

where V_0 is the surface void space fraction, ρ_∞ is the density of the completely compacted country rock and ρ_{surf} is the surface country rock bulk density. For any depth change dh , $dP = \rho_c g dh$, where g is the acceleration due to gravity and integration of equations (1-3) gives:

$$\rho_c(h) = \rho_\infty / [1 + \{V_0 / (1-V_0)\} \exp(-\lambda \rho_\infty g h)] \quad (4),$$

$$P(h) - P_{\text{surf}} = \lambda^{-1} \ln [V_0 + (1-V_0) \exp(\lambda \rho_\infty g h)] \quad (5),$$

where P_{surf} is the surface atmospheric pressure. Thus, ρ_c and P can both be specified as a function of h using ρ_∞ , λ and V_0 . Data for Earth's basaltic volcanic areas [3, 4] fit to $\rho_\infty = 2900 \text{ kg/m}^3$, $\lambda = 1.18 \times 10^{-8} \text{ Pa}^{-1}$ and $V_0 = 0.24$. λ , being independent of gravity, will be the same for Venus as for Earth. For the upper 40 km of the Venus lithosphere, $\rho_\infty \sim 3000 \text{ kg/m}^3$ seems appropriate [8]. We now assume that basaltic magmas on Venus contain at least some volatiles, and calculate the gas exsolution in a rising magma as a function of depth. This gives the surface void fraction, V_0 , from which we compute $\rho_c(h)$ using eq. (4). The ability of batches of melt to reach the surface depends on the difference between the rates at which melt and country rock densities decreases upwards. By analogy with terrestrial basalts [9], we investigate total gas contents in Venus magmas up to $N_{\text{TW}} = 1 \text{ wt\%}$ for water & $N_{\text{TC}} = 0.5 \text{ wt\%}$ for CO_2 . Experimental solubility data can be represented by [10]:

$$N_{\text{dc}}(P) = 2.3 \times 10^{-11} (P/\text{Pa}) \quad (6), \quad N_{\text{dw}}(P) = 6.8 \times 10^{-8} (P/\text{Pa})^{0.7} \quad (7).$$

The amounts of the volatiles exsolved at any given pressure, N_{ec} and N_{ew} , respectively, are then:

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$$N_{ec}(P) = N_{tc} - N_{dc}(P) \quad (8), \quad N_{ew}(P) = N_{tw} - N_{dw}(P) \quad (9).$$

If either $N_{ec}(P)$ or $N_{ew}(P)$ is negative, the magma is not yet saturated in this component, and the value is set to zero. The bulk density β of a suspension of these exsolved volatiles in material of compacted density ρ is found by combining the fractional volumes of the components (e.g., [10]):

$$\beta^{-1} = [(Q/T)/P] [(N_{ec}/m_c) + (N_{ew}/m_w)] + [(1 - N_{ec} - N_{ew})/\rho] \quad (10),$$

where $Q = 8341 \text{ J kg}^{-1} \text{ K}^{-1}$, T is the magma temperature ($\sim 1200 \text{ K}$), & m_c , m_w are the molecular weights of CO_2 and H_2O , 44 and 18, respectively. We identify β with ρ_{surf} and set $\rho = \rho_\infty = 3000 \text{ kg/m}^3$, since it is the bulk density of the country rock formed on solidification that we require.

Results Calculations were carried out for 3 surface atmospheric pressures: lowland plains, tessera blocks, and the mean surface of Lakshmi Planum, $P_{\text{surf}} = 8.52$, 7.09 and 5.64 MPa , respectively. The table shows examples for 3 values of N_{tc} for water-free magma erupted at $P_{\text{surf}} = 7.09 \text{ MPa}$. In the first two columns, for $N_{tc} = 0.15 \text{ wt\%}$, all values of β_m are smaller than the corresponding values of ρ_c : this melt will rise buoyantly all the way to the surface. In the second two columns, for $N_{tc} = 0.25 \text{ wt\%}$, magma is buoyant at all depths below about 1700 m and also at depths shallower than $\sim 495 \text{ m}$; in between it is negatively buoyant. Thus a rising magma batch should be trapped with its center at 1700 m depth. A reservoir should grow vertically, extending as far below the neutral buoyancy level as above it. If no other factors were relevant, growth would go on until the reservoir top reached a depth of 495 m below the surface (giving a maximum vertical extent of about 2.4 km) at which point buoyant magma would automatically leave it to migrate up to the surface. The final 2 columns of the table, for $N_{tc} = 0.35 \text{ wt\%}$, show a chamber center at a greater depth of $\sim 2900 \text{ km}$, the potential vertical extent being $\sim 5.4 \text{ km}$. Other calculations show chamber centers to get deeper as P_{surf} decreases and as both (or either) gas contents increase. Also, the minimum volatile content allowing a chamber to form at all decreases with decreasing P_{surf} . So magma chambers on Venus are more likely to form in volcanoes at high elevations or in volcanoes with gas-rich magmas; also, they will be relatively larger in volcanoes forming at high elevations for given magma volatile contents.

References [1] Sparks, R.S.J. (1978) J.V.G.R. 3, 1. [2] Head J.W. & Wilson, L. (1986) J.G.R. 91, 9407. [3] Hill, D.P. (1969) Bull. Seis. Soc. Am. 59, 101. [4] Gudmundsson, A. (1987) J.V.G.R. 34, 65. [5] Rubin, A.M. & Pollard, D.D. (1987) Ch. 53 in U.S.G.S. Prof. Pap. 1350 [6] Parfitt, E.A. (1991) "Shape of dikes" (this vol.) [7] Tait, S.R., Jaupart, C. & Vergnolle, S. (1989) EPSL. 92, 107. [8] Hess, P.C. & Head, J.W. (1990) pers. comm. [9] Bas. Volc. Study Proj. (1981) [10] Wilson, L. & Head, J.W. (1981) J.G.R. 86, 2971.

Table Depth variation of bulk density (kg/m^3) of country rock (ρ_c) and magma (β_m) for 3 total CO_2 contents, N_{tc} , in water-free Venus magma. $P_{\text{surf}} = 7.09 \text{ MPa}$. 'b' & 't' imply magma is locally buoyant/trapped in country rock, respectively. Underlines mark center of potential chamber.

	$N_{tc} = 0.15 \text{ wt\%}$			$N_{tc} = 0.25 \text{ wt\%}$			$N_{tc} = 0.35 \text{ wt\%}$		
depth/m	ρ_c	β_m		ρ_c	β_m		ρ_c	β_m	
0	2661	2422	b	2454	2250	b	2276	2100	b
250	2684	2558	b	2488	2441	b	2318	2328	t
500	2705	2612	b	2520	2526	t	2358	2439	t
1000	2744	2660	b	2579	2605	t	2433	2547	t
1500	2778	2682	b	<u>2633</u>	<u>2642</u>	t	2502	2599	t
2000	2808	2694	b	2680	2663	b	2563	2630	t
2500	2834	2700	b	2722	2677	b	2618	2650	t
2750	2846	2700	b	2741	2682	b	<u>2643</u>	<u>2658</u>	t
3000	2857	2700	b	2759	2686	b	2667	2664	b
3500	2877	2700	b	2791	2693	b	2710	2674	b
4000	2894	2700	b	2819	2698	b	2749	2682	b