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Lava Fountain Heights at Pu'u 'O'o, Kilauea, Hawaii: Indicators of Amount and Variations of Exsolved Magma Volatiles

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We review the factors determining lava fountain heights in Hawaiian-style basaltic eruptions such as those occurring during the recent series of eruptive episodes at the Pu'u 'O'o vent, east rift zone of Kilauea Volcano, Hawaii. Numerical solutions to the equations describing the fluid dynamics of such eruptions predict that lava fountain heights, which are indicators of the velocity of magmas in vents, should be controlled much more strongly by amounts of exsolved volatiles than by any other factors. The next most important factor is the width of the conduit system, which determines frictional losses and can be characterized by the volume flux of magma. The diameter of the surface vent required to accommodate a given discharge (i.e., instantaneous volume rate of eruption) is also a function of exsolved magma volatile content but is less dependent on this factor than is the fountain height. We simulate fountain heights for typical discharges at Pu'u 'O'o and find implied exsolved gas contents very close to those determined by other methods. The corresponding predicted vent diameters are comparable with (and somewhat smaller than) the observed diameter of the Pu'u 'O'o vent. The discrepancy is probably a consequence of processes occurring in the lava pond which is present over the vent during eruptions. The variation of fountain height with time during eruptive episodes can be used as a measure of changing exsolved magma volatile content, which can be related to processes occurring in the subsurface dike system.

1. INTRODUCTION

The Hawaiian style of volcanic activity involves the relatively steady discharge of magma, which is disrupted below or at the surface into a mixture of released gas and pyroclasts. The pyroclasts in the resulting fountains have a range of grain sizes sufficiently coarse that little of the pyroclastic material is entrained into a convecting cloud over the vent [*Wilson and Head*, 1981]. Most of the material returns to the surface to form pyroclastic cones and rootless flows or to feed lava ponds or lava flows. Recent activity along the east rift zone of Kilauea volcano at Pu'u 'O'o illustrates some of the basic characteristics of Hawaiian-style eruptions: (1) the formation of sharply defined fountains whose heights are measured in tens to hundreds of meters (~200 m is typical for the recent Pu'u 'O'o activity), and 2) relatively high discharges (~100 m^3/s is typical for Pu'u 'O'o). Theoretical studies [*Wilson and Head*, 1981] show that fountain height is controlled by discharge and exsolved gas content of the magma. Detailed studies of the Pu'u 'O'o activity [*Wolfe et al.*, 1987; *Greenland*, 1987; *Neal et al.*, 1987] and our own observations allow us to test the theoretical predictions and to address the questions (1) which factor is most important in determining fountain height?, (2) can fountain height be used as a measure of the proportion of gas erupted?, and (3) can these parameters be used to determine the geometry of the vent and conduit near the surface?

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2. THE RELATIVE IMPORTANCE OF DISCHARGE AND EXSOLVED GAS CONTENT IN DETERMINING FOUNTAIN HEIGHT

To illustrate the relative importance of discharge and exsolved gas content in determining fountain height, we examine first the case of lava effusion and fountaining in which the magma contains no gas. We outline the conditions required for the fountains resulting from this case to achieve the average observed fountain height of 200 m. For gasless magma rising to the surface the critical factors determining rise speed have been shown to be magma density and pressure gradient and that determining volume flux to be conduit geometry [*McGetchin and Ullrich*, 1973; *Wilson and Head*, 1981]. When most pyroclasts are sufficiently coarse not to be entrained into a convecting eruption cloud over the vent, fountain height H is related to the eruption velocity in the vent u by the ballistic equation:

TABLE 1. Gas-Free Eruption Parameters for a 10-m-radius Circular Conduit for Various Values of the Driving Pressure Gradient dQ/dL in a Magma With Newtonian Viscosity 100 Pa s

dQ/dL, Pa/m	p', kg/m^3	u, m/s	Re	V, m^3/s	H, m
1	0.1	0.125	63	40	0.0007
3	0.3	0.375	188	120	0.007
10	1	2	1,000	63	0.204
30	3	3.46	1,732	1,090	0.599
100	10	6.33	3,200	1,990	2.04
300	30	10.95	5,500	3,450	6.12
1,000	100	20	10,000	6,300	20.4
3,000	300	34.64	17,000	10,900	61.2
10,000	1,000	63.24	32,000	19,900	200.0

The p' is the density difference between the magma and the country rock in cases where the eruption is driven solely by magma buoyancy, u the mean magma rise velocity, Re the Reynolds number of the motion, and V the discharge (volume flux) of magma. H is the height to which the resulting liquid fountain would rise.

$$H = u^2/2g \tag{1}$$

where g is the acceleration due to gravity [*Wilson and Head*, 1981]. In a circular tubelike conduit, u is determined by the driving pressure gradient dQ/dL, the tube radius r_ω, and the physical properties of the magma. In the case of no gas in the magma,

$$u = \left[\frac{r_\omega}{f\,p} \; dQ/dL \right]^{1/2} \tag{2}$$

for turbulent flow, where f is a friction factor close to 0.01 for motion in a rough tube [*McAdams*, 1954] and p is the density of the essentially incompressible magmatic liquid; alternatively,

$$u = \frac{(dQ/dL) \;\; r_\omega^2}{8\,\mu} \tag{3}$$

for laminar flow, where μ is the Newtonian viscosity. At Pu'u 'O'o the geometry of the uppermost part of the vent was described as a 20-m-diameter tube [*Wolfe et al.*, 1987] throughout much of the eruption sequence, and so we take the surface radius of the vent to be a maximum of 10 m. Under gas-free conditions the simplest possible conduit geometry is a straight-sided tube with constant radius, r_ω, equal to the surface vent radius. Table 1 illustrates fountain height for a range of conditions for a gasless magma rising through a tube of this size. Note that if we require the volume flux to match that typical of Pu'u 'O'o events, about 100 m^3/s, the implied magma rise speed is about 0.4 m/s and the fountain height would be less than 1 cm! Alternatively, if we match the average fountain height of 200 m, this requires the volume flux to be 20,000 m^3/s, 100 times the maximum flux observed. These comparisons illustrate the extent to which exsolved magma gas content, rather than discharge, must be the dominant factor in determining fountain height.

3. THE ROLE OF EXSOLVED GAS IN DETERMINING FOUNTAIN HEIGHT

The relations among exsolved gas content, effusion rate, and fountain height were investigated in general terms by *Wilson and Head* [1981]. Measurements of the heights and discharges for the Pu'u 'O'o fountains can be used to test these general relations and to predict the exsolved gas contents of the magmas. In addition, gas contents measured during the eruptions can be used to test these relations quantitatively. The calculations of *Wilson and Head* [1981] further predict the size of the conduit once its general shape (circular, rectangular) has been chosen, and several observations of the size of the vent during the Pu'u 'O'o eruptions can be used to check these predictions.

The relations between discharge (volume flux) and fountain height are shown in Figure 1 for a variety of gas contents. Values were calculated using the numerical methods (equations (16), (17) and (18)) of *Wilson and Head* [1981] for a circular conduit geometry and for ranges of values of surface vent radius and total magma gas content likely to be relevant to Hawaiian eruptions. Note the very weak dependence of fountain height on discharge for a given exsolved gas content, except at extremely low discharges (less than about 25 m^3/s) where the values of r_ω would be so small that wall friction would become very important. For example, for an exsolved gas content of 0.2 wt % H_2O, fountain height varies by less than 16% (about 75–87 m) over a range of discharges differing by a factor of four (50–200 m^3/s). For higher gas contents (0.6 wt % H_2O), fountain height varies by less than 17%

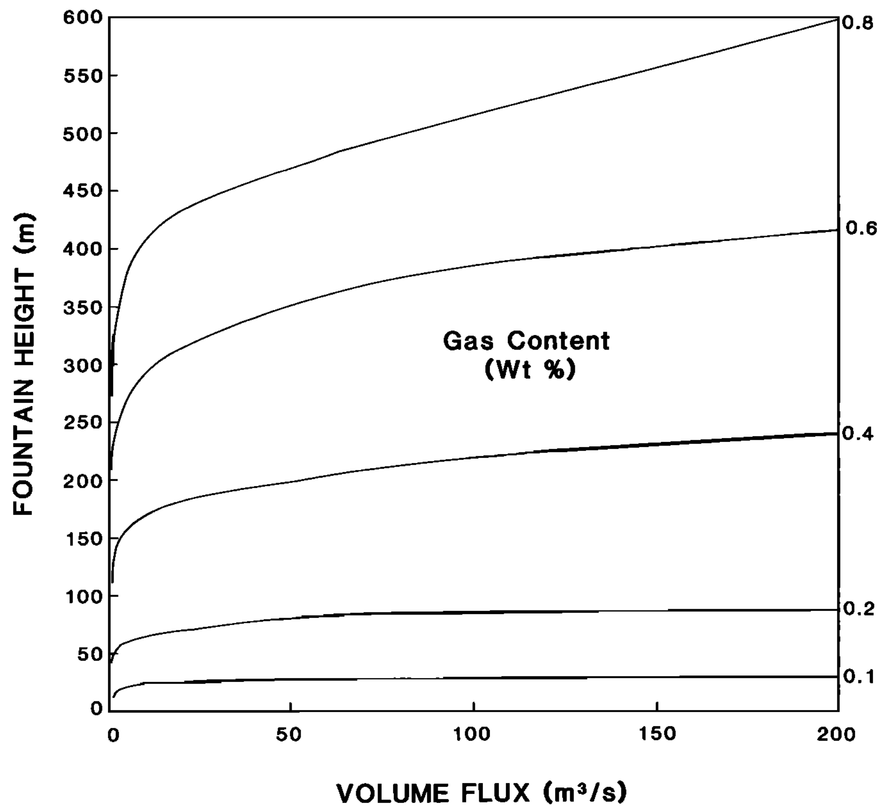

Fig. 1. Variations of predicted fountain height with erupted magma volume flux for five values of exsolved magma volatile content. For convenience, the volatile is assumed to consist entirely of H_2O. For Hawaiian magmas, fountain height depends much more strongly on gas content than volume flux except at very low fluxes or high gas contents.

(about 355–415 m) over the same range of discharges. For the Pu'u 'O'o eruptions, the highest observed fountains, about 400 m [*Wolfe et al.*, 1987], indicate an exsolved gas content of between 0.6 and 0.8 wt % H_2O for a wide range of possible discharges, while the average fountain height, about 200 m, indicates an exsolved gas content of 0.4 wt % H_2O for all discharges in excess of 50 m^3/s.

Greenland [1987] reports measurements that indicate that the current east rift magma releases approximately 0.4 wt % total gas upon eruption. These measurements agree closely with our predictions based on the typical observed fountain heights and theoretical relations between gas content and fountain height (Figure 1). This agreement suggest that fountain height can be used as a reliable indication of exsolved magma gas content for a wide range of commonly occuring effusion rates.

4. Variation of Fountain Height in Individual Episodes as Indicators of Gas Content Variability

Fountain heights during episodes 2–20 ranged from a few meters to a maximum height of almost 400 m [*Wolfe et al.*, 1987]. Such heights suggest a range of exsolved magma gas contents from less than 0.1 wt % to more than 0.6 wt % (Figure 1). During individual episodes, fountain height often increased with time; fountain heights in the first few tens of minutes to 2 hours were often less than 10 m, and those in later periods achieved heights of tens to several hundred meters (Figure 2). Fountains terminated much more abruptly, either suddenly or with sporadic activity in the last 3–10 min of the episode [*Wolfe et al.*, 1987]. Taken together and interpreted in terms of the relations in Figure 1, these observations strongly suggest that most episodes

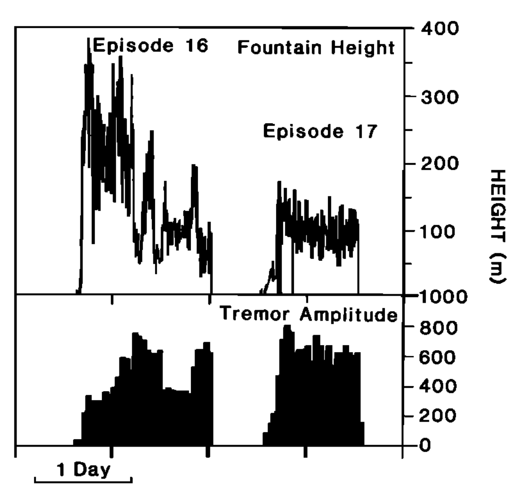

Fig. 2. Variation of fountain height with time during episodes 16 and 17 of the Pu'u 'O'o eruption [from Wolfe et al., 1987]. Large variations on a time scale of as little as 2 hours commonly occur.

were characterized by initial fountains of gas-poor magma (<0.1 wt %), followed by fountains of more gas-rich magma (0.2–0.6 wt %) until the eruptive episode ended. The initial volume of gas-poor magma is reasonably explained as that left in the immediate subvent part of the system at the end of the previous eruptive episode. However, the rapid cessation of both fountaining and lava output at the end of an eruptive episode indicates that the magma left in the immediate subvent region is gas-rich. Thus much of this gas must be lost during the repose period, which ends with the onset of low, gas-poor fountains at the start of the next episode.

Variations in height during the main stage of fountaining provide evidence for varying gas content with time. In episode 16, which lasted about 1.5 days, fountain height during the main stage varied from about 40 to 400 m. In the first 12 hours, fountain height varied from 100 to 400 m but centered on an average of about 200 m. In the last 12 hours, fountain height varied from about 40 to 200 m, with an average of about 100 m. For episode 16, these data suggest that (1) gas contents can vary considerably over short time periods (0.3–0.6 wt % in less than 3 hours), and (2) gas contents can show systematic variations during the main stage of eruptive episodes (an average of 0.4 wt % during the first 12 hours, and 0.2–0.25 wt % during the last 12 hours).

The calculated magma velocity in the deeper parts of the conduit system is of the order of 0.1 m/s [*Wilson and Head*, 1981]. This velocity, together with the evidence for varying gas content with time, implies that exsolved gas content in the magma in the transport system varies on at least two scales: (1) lateral distances in the near-vent dike system measured in hundreds of meters, and (2) lateral distances in the rift system of the order of several kilometers.

The smaller-scale variations may be due to gas loss from some parts of the dike into the overlying rift system during repose periods. The large-scale variations suggest the presence of more substantial magma reservoirs at intervals along the dike. Since gas bubbles can migrate only vertically in the liquid, magma moving laterally during eruptive episodes carries with it the memory of the amount of gas lost during repose periods.

In episode 17, which lasted about 1 day, fountain height after the first 6 hours ranged from 50 to 160 m, averaging about 100 m (Figure 2). Compared with episode 16, (1) short-term variation of fountain height was much less dramatic, (2) longer-term varation did not occur (although the main stage of episode 17 lasted about as long as each of the two parts of episode 16), and (3) the average fountain height was less.

Considerable variability in height characterises the sequence of Pu'u 'O'o fountains as a whole, but later episodes tend to have higher average fountain heights than do earlier ones. This observation suggests a trend of increasing gas content during the Pu'u 'O'o eruption.

In conclusion, observed variations in fountain height strongly suggest that (1) magma degasing takes place in the vent area during repose periods, (2) there is a general trend of increased gas content in the Pu'u 'O'o eruptions with time, and (3) there are two scales of gas content variation in the magma that suggest differences in the gas content related to short distances (hundreds of meters) and longer distances (kilometers) in the magma supply system.

5. Size and Geometry of Conduit

Lava discharge is related to conduit size and geometry. The calculations of *Wilson and Head* [1981] show the theoretical relations between the size and shape of the conduit and the discharge and predict that the vent diameter required to accommodate a given discharge with the gas exit pressure equal to the atmospheric pressure depends only weakly on exsolved gas content. The observations at Pu'u 'O'o can be used to check these theoretical predictions. Figure 3 illustrates the predicted relation between volume flux and vent diameter for a range of gas contents relevant to the Pu'u 'O'o activity, again using the methods of *Wilson and Head* [1981]. If we take typical volume fluxes for Pu'u 'O'o (~100 m^3/s [*Wolfe et al.*, 1987] and typical gas contents (~0.3–0.4 wt % [*Greenland*, 1987], and estimates from section 4), we would predict a vent diameter of about 8 m on the basis of the relationships in Figure 3. If we consider extreme values for these variables of 0.8 wt % gas and 200 m^3/s (much greater than any volume flux reported for episodes 1–20 [*Wolfe et al.*, 1987], the vent diameter would be 14 m, still considerably less than the 20-m -diameter maximum vent size reported by *Wolfe et al.* [1987] and *Neal et al.* [1987].

How can we account for this apparent discrepancy? It is certainly not related to any assumptions about the gas pressure in the vent. If exit pressures were greater than 1 bar (in cases where rock rigidity restricts the neck of the vent, for example) the predicted vent sizes would be smaller (although wall erosion could then occur to enlarge the upper part of the vent to the predicted size).

We suggest that the observed vent diameter of 20 m is related more to the geometry and dynamics of the lava pond within the cone than to the actual diameter of the conduit below the lava pond. This is supported by the fact that the vent diameter was smaller in the earlier episodes (prior to lava pond development). Some lava must constantly drain downward around the edges of the vent orifice to be entrained and recycled into the ascending jet of gas and magma clots. This process has yet to be analyzed in detail, but it is clear that the system will reach equilibrium at a greater vent diameter than is needed if no recycling occurs, since the appropriate cross-sectional area must be available for both the downgoing and reemerging lava fluxes. We conclude that the size of the discrepancy between our predicted vent diameter and that observed is suffi-

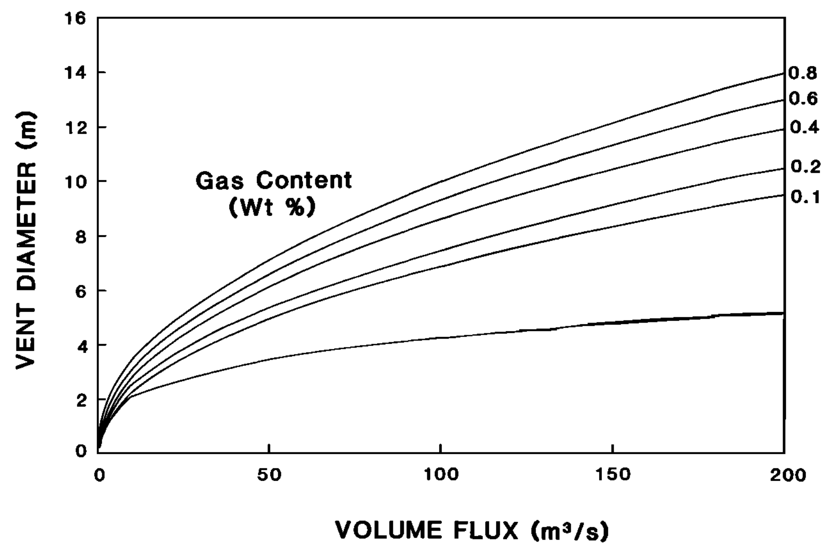

Fig. 3. Variation of predicted vent diameter with volume flux of erupted magmas for five values of exsolved magma volatile (H_2O) content. It is assumed that the gas phase decompresses to atmospheric pressure at the vent. The unlabeled curve corresponds to eruption of gas-free magma. The dependence of vent diameter on gas content is generally somewhat greater than that on volume flux.

ciently great to suggest that recycling of lava pond material is an important process which requires further study.

6. CONCLUSIONS

On the basis of theoretical calculations and observations at Pu'u 'O'o we show that (1) volume flux, rather than exsolved gas content, is the most important parameter determining equilibrium vent diameter, (2) recycling of lava in ponds around vents is probably an important process, (3) for a given exsolved gas content, fountain height is relatively insensitive to large variations in volume flux, (4) fountain height is very sensitive to changes in exsolved gas content and can be used to estimate variability in exsolved gas content, and (5) by applying this technique to observations of fountain height variations at Pu'u 'O'o we conclude that gas depletion takes place in the conduit beneath the vent during repose periods and that there is a general increase in magma gas content over the first 20 episodes of the Pu'u 'O'o eruption.

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