BASALTIC PYROCLASTIC ERUPTIONS: INFLUENCE OF GAS-RELEASE PATTERNS AND VOLUME FLUXES ON FOUNTAIN STRUCTURE, AND THE FORMATION OF CINDER CONES, SPATTER CONES, ROOTLESS FLOWS, LAVA PONDS AND LAVA FLOWS

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Abstract


In basaltic pyroclastic eruptions, two variables - magma gas content and magma volume flux — determine the detailed dynamic structure of the fountain and the size distribution of clasts within it. The fountain structure and clast size distribution in turn determine the nature of the resulting deposits, whether these be stationary pyroclastic constructs or active lava flows. Although the physical relationships between gas content and clast size are not fully understood, empirical data are available for basaltic eruptions. Fountain dynamic structure is determined by the velocity profile at any given pressure level and the maximum spread angle of the fountain from the vertical. These two parameters completely determine the paths of pyroclasts in the fountain and their ultimate resting places. The combination of the pyroclast size and the spatial distribution determines the clast number density and thus the opacity of the fountain and the ability of the pyroclasts to cool in their local fountain environment. For a given set of conditions, two factors thus become important in determining the structure and morphology of pyroclastic deposits: local temperature and accumulation rate. For example, in typical basaltic pyroclastic eruptions, the majority of pyroclasts remain inside the optically thick central part of the fountain, undergo minimal cooling, and return to the surface to coalesce and contribute to a lava pond or lava flow. In the optically thinner outer parts of the fountain, clasts undergo relatively more cooling and return to the surface to contribute to the building of the pyroclastic cone (if the accumulation rate is low) or to form rootless flows (if the accumulation rate is high and minimal further cooling occurs). The relationships between these various parameters are investigated for Hawaiian-style eruptions in general and applied qualitatively to the interpretation of post-eruption deposits.

Introduction

Basaltic explosive volcanic activity involves the intermittent to relatively steady discharge of magma, which is disrupted below or at the surface into a mixture of released gas and pyroclasts. The pyroclasts have a sufficiently coarse range of grain sizes that little of this material is entrained into a convection cloud over the vent and most of the pyroclasts form a fountain-like
structure, through which they return on near-ballistic paths to the surface to form a variety of products and features in the vicinity of the vent. Features commonly formed at or near the vent include cinder cones, spatter cones, rootless flows, lava ponds, and lava flows.

Theoretical treatments of the relative roles of effusion rate and gas content in determining fountain height predict that gas content is the dominant factor under almost all conditions, and that, except at very low magma effusion rates, fountain height is almost independent of effusion rate. Thus, fountain height can be used to estimate magma gas content quite accurately if the conduit geometry is known (Wilson and Head, 1981), and can give an approximate estimate even when the discharge rate and vent geometry are unknown. As an extreme example, gasless basaltic magmas erupted at commonly observed volume rates (~ 100 m³/s) and driven to the surface by excess pressure gradients in the range 10²-10³ Pa/m (which should cover most occurrences on Earth – Wilson and Head, 1981) would require circular vents only about 3–6 m in diameter, or elongate fissure vents only about 1–2 m wide. Such eruptions would produce fountains only centimeters to at most a few tens of centimeters high. In contrast, theoretical analyses predict that exsolved magma gas contents of, for example, 0.4 wt.% should result in fountain heights of about 200 m. These theoretical predictions have been confirmed (Head and Wilson, 1987) by observations and measurements during a series of eruptions at Pu‘u O‘o (Greenland, 1987; Wolfe et al., 1987) on the Kilauea East Rift Zone. Observations of fountain height can thus be used as a tool to help understand the variability of magma gas content within an eruptive episode and to detect longer-term volatile content trends in an eruption sequence.

In more detail, basaltic explosive volcanic eruptions can be described in terms of two features: (1) detailed fountain dynamic structure, (Fig. 1); and (2) near-vent pyroclastic deposits (e.g., cinder cones, spatter cones, rootless flows, lava ponds, lava flows). For typical basaltic magma viscosities, these two eruption characteristics are almost entirely determined by the same two volcanic system variables, magma gas content and effusion rate. For example, these two variables determine the dynamic structure of the fountain by influencing: (1) the size distribution of pyroclasts; (2) the mean upward velocity of pyroclasts in the vent; (3) the spread angle from vertical of pyroclasts leaving the vent; and (4) whether an eruption is relatively steady (hawaiian lava-fountain style) or episodic (strombolian-style) (Wilson and Head, 1981; Vergniolle and Jaupart, 1986). The fountain dynamic structure is in turn closely linked to the nature and abundance of near-vent pyroclastic deposits. In this paper we explore the relationship of the two fundamental volcanic system variables (magma gas content and effusion rate) to basic eruption characteristics (fountain dynamic structure and near-vent pyroclastic deposits) in order to understand the physics of basaltic volcanic eruptions, and to interpret the nature of previous volcanic eruptions on the basis of their post-eruption deposits.

**Basic considerations**

**Clast size and fountain structure**

Steady fountaining is a defining characteristic of hawaiian-style eruptions and involves a mass flux in excess of a threshold value and a gas content which can be inferred from fountain height. The two main manifestations of variations in gas content and effusion rate are (1) clast size distribution and (2) height and structure of the fountain.

No theoretical model linking clast size distribution to gas exsolution and breakup of magma has yet been developed because the processes involved are complex and not fully understood. Some factors must include gas nucleation, bubble formation and coalescence, gas diffusion, deformation of the host liquid (which is related to rheology), and the interplay of gas exsolution and magma rise rate (Sparks, 1978). How-
ever, empirical relations can certainly be found between clast size distributions, magma composition and magma volatile content (e.g., Walker, 1973, 1980; Self et al., 1974; Self and Sparks, 1978; Wright et al., 1980b), and these form a practical basis for attempts to classify eruption styles using grain size distributions and clast dispersal (Walker, 1973; Wright et al., 1980a).

A velocity profile and maximum spread angle from the vertical can be defined within a pyroclastic fountain at any given pressure level (Fig. 1). The pressure level in the vent will be either atmospheric or slightly greater than atmospheric (Wilson and Head, 1981; Wilson and Mougins-Mark, 1985). The Reynolds number of essentially all erupting gas-pyroclast mixtures is high enough that the velocity profile in the rigid-walled conduit system at and below the vent is nearly flat (Knudsen and Katz, 1958), and the maximum spread angle at which clasts emerge through the vent can be predicted theoretically for any given magma gas content and mass flux using numerical models of the eruption process (Wilson and Head, 1981; Wilson et al., 1980). The combination of the spread angles and velocities then determines the paths of pyroclasts in a fountain (the fountain's dynamic structure), and thus their flight times, cooling times, and accumulation rates on the ground (Wilson and Head, 1981).

Observations of convecting plumes above and downwind of pyroclastic fountains show that there is an interaction between entrained air and at least the smaller clasts in a fountain, as evidenced by the effects of atmospheric wind profiles on fountains (Fig. 1). No studies have yet determined the clast size below which the drag forces due to gas motions in fountains severely perturb the paths of scoria from being near-ballistic, but empirical evidence shows that for typical basaltic deposits the convectively transported clasts are in the minority in terms of the total mass involved (Self et al., 1974). We infer that, when either volume flux or magma gas content (or both) are larger than usual, there is a stronger interaction between clasts and gas phase. As the amount of exsolved gas increases, magma fragmentation also increases and mean clast size decreases; as mass flux becomes larger, clasts become more crowded, stay hotter longer on average and lose more heat locally by conduction and convection to surrounding gases than is radiated to great distances. We predict that it is this increased degree of coupling between clasts and gas that permits basaltic plinian eruption columns (Williams, 1983; Walker et al., 1984) and ba-
Fig. 2. Flow chart illustrating factors important in the dynamic structure of pyroclastic fountains and in the resulting post-eruption facies, deposits, and morphology.

Fig. 3. The dependence of local temperature on gas content and volume flux. Contours of temperature are qualitative and are based on calculations by Wilson and Head (1981). For a fixed-volume flux, the temperature decreases with increasing gas content because of wider clast dispersal, decrease in optical thickness, and more efficient cooling. This trend is partially offset by the fact that increased gas content also leads to increased particle disruption, decreased clast size and greater opacity; this leads to the curved temperature contours.

Fig. 4. The dependence of local accumulation rate on gas content and volume flux. For a given gas content, the ranges of clasts are determined, but the number that land per second increases with increasing mass flux. For a fixed-volume flux, the ranges of clasts increase with increasing gas content, so that they are distributed over a larger area, and the local accumulation rate decreases. Contours of local accumulation rate are curved because accumulation rate is linearly proportional to volume flux, but is a nonlinear function of gas content.

saltic pyroclastic flows (Taylor, 1963; Williams and Curtis, 1964; Johnson et al., 1972) to form. Nevertheless, such cases are rare; we deal here with the circumstances applying to the majority of basaltic eruptions.

We consider initially the case of pyroclastic fountaining with no wind. Within the fountain, the combination of pyroclast sizes and their spatial distribution determines the clast number density and thus the opacity of the fountain and hence the ability of the pyroclasts to cool in the local fountain environment (Wilson and Head, 1981). The opacity of the fountain can commonly be observed as a continuum of color and optical thickness from the fountain interior to exterior (Fig. 1). For example, in the fountain center, the clast number density is high, the fountain is optically thick, cooling is inhibited, and the color of the fountain is generally golden-yellow. Further toward the fountain exterior, the clast number density is intermediate, the fountain is optically thinner, cooling is more efficient, and the color of the fountain is generally orange to red. At the edge
of the fountain, the clast number density is low, the fountain is optically thin, cooling of clast exteriors is very efficient, and the color of the fountain is generally brown to black (i.e., color is dominated by reflected light, rather than thermal emission).

In a completely symmetrical fountain, an exterior observer viewing the central part of the fountain is seeing some average of the optical density, because one observes the inner, optically thick portion through the optically thin outer parts of the fountain between the observer and the fountain core (Fig. 1). In asymmetrical fountains, often caused by strong local winds, conditions can modify the outer optically thinner portions of the fountain and reveal the details of the inner optically thick core to the observer.

**Local temperature and accumulation rate**

For a given set of conditions, two factors thus become important in determining the structure and morphology of deposits resulting from pyroclastic fountains: (1) the local temperature of the clasts as they land; and (2) the accumulation rate of the clasts. These two factors are strongly dependent on the fundamental parameters gas content and volume flux (Fig. 2).

The general dependence of local temperature on gas content and volume flux is shown qualitatively in Figure 3, based on some specific calculations by Wilson and Head (1981) for lunar eruptions. The combination of size distribution and spatial distribution determines the number density and hence the opacity of the fountain and the ability of the clasts to cool. For a fixed gas content (and hence clast size distribution and dispersal), the local temperature increases with increasing volume flux due to greater clast number density and, hence, fountain opacity (Fig. 3). For a fixed volume flux, the temperature decreases with increasing gas content because of wider clast dispersal, decrease in optical thickness, and more efficient cooling. This trend is partially offset by the fact that increased gas content also leads to increased particle disruption, decreased clast size and greater opacity; this leads to the curved temperature contours in Figure 3.

The dependence of accumulation rate on gas content and volume flux is shown in Figure 4. For a given gas content, the ranges of clasts are determined, but the number that land per second increases with increasing mass flux. For a fixed volume flux, the ranges of clasts increase with increasing gas content, so that they are distributed over a larger area, and the local accumulation rate decreases. Contours of accumulation rate (Fig. 4) are curved because accumulation rate is linearly proportional to volume flux, but is a nonlinear function of gas content.

It is useful to think of an eruption episode in terms of a movie which has recorded and integrated the individual frames or snapshots into a record of the entire sequence of events. Observation of an individual frame or snapshot (for example, Fig. 1) shows that there is not a single temperature throughout the eruption fountain. For a given volume flux and gas content, temperature and accumulation rate will vary with distance from the central part of the vent, producing the dynamic structure seen in
Fig. 6. Pyroclastic fountains and deposits. a. Hawaiian fountain showing variations in fountain dynamic structure (Fig. 1) and a range of deposits (for example, note rootless flow on the right); details of fountain structure, color, and deposits are described in the text and the trends are illustrated as line (1) on Figure 5. b. Highly collimated pyroclastic fountain at Pu'u 'O'o. Most pyroclasts cool only slightly in the optically thick (red to orange) part of the fountain and fall back into the lava pond (within the cone surrounding the vent) which is overflowing to feed a flow. Details are described in the text and the trend is shown as line (2) on Figure 5. Photograph by Brett Uprichard, Honolulu Magazine, April, 1983. c. Pu'u 'O'o Hawaiian fountain showing the influence of wind profile distorting the distribution of small pyroclasts in the optically thin cooler parts of the fountain (brown and black) downwind (toward the right). Details are described in the text and the trend is shown as line (3) on Figure 5. Photograph by Noel Black.

Figure 1. Thus, a given point on Figures 3 and 4 is an average; the inner part of the fountain would be hotter and accumulation rates higher, while the outer part of the fountain would be cooler and accumulation rates lower.

We now examine each of these several variables systematically to understand the range of conditions in which a variety of deposits and landforms might be produced.

Application of basic considerations to typical eruptions

The relationship between mean pyroclast temperature and pyroclast accumulation rate defines a realm in which occur most types of pyroclasts and pyroclastic accumulations (Fig. 5). For cold clasts, the accumulation rate is irrelevant, and unwelded cinder/scoria deposits are formed. For warm clasts, low accumulation rates yield plastic cinders, but high accumulation rates yield completely welded spatter because cooling between successively arriving clasts is minimized. Moderate accumulation rates yield partly welded spatter. For hot clasts, low accumulation rates yield individual fluid ‘plops’. High accumulation rates yield lava flows and/or lava ponds through clast coalescence because there is minimum cooling of a large volume of fragments. This combination of hot
pyroclasts and very fast accumulation means that most of the fragments have stayed within the optically thick part of the fountain, and are thus more likely to produce lava flows and ponds.

For fast accumulation rates, cold clasts will produce brittle cinder accumulations which commonly result in cinder and scoria cones. Fast accumulation of warm clasts will produce welded spatter deposits in the form of spatter cones or spatter carapaces. Fast accumulation of hot clasts will lead to coagulation of fluid particles, forming lava flows or lava ponds.

Even when volume flux and gas content are fixed, a range of conditions will occur at any one time during an eruption, and fragment temperature and accumulation rate will vary with radial distance from the vent (Fig. 1). For example, the vast majority of the pyroclasts will land hot and fluid at the base of the central part of the fountain, will coalesce to form a lava flow, and will flow away from the vent region. That this is the case is demonstrated by the orders of magnitude difference between the volume of lava flow deposits emanating from the vent, on the one hand, and the volume of the cone and pyroclastic deposits surrounding the vent, on the other (Wood, 1980). At the same time, the variable clast spread angle and the velocity profile within the fountain mean that, toward its outer edge, optical density is low, cooling is maximized, and accumulation rate is minimized, producing accumulations of brittle cinders usually in the form of cinder cones. An extreme case is illustrated by the very low mass flux basaltic eruptions which commonly produce strombolian activity. Here much of the pyroclastic material lands hot, but because of the very low mass flux, and thus accumulation rate, a landed pyroclast cools significantly be-
fore the arrival of more material in the same location. This highlights the importance of accumulation rate as well as clast temperature. Thus, a given eruption snapshot (Fig. 1) is mapped as a line linking a finite range of conditions in Figure 5. In the next section we examine a series of eruption snapshots in order to map out their position on Figure 5 in detail and to begin to develop general relationships between pyroclast types and deposits, and pyroclast temperatures and accumulation rates.

A typical Hawaiian-style basaltic pyroclastic eruption (Fig. 6a) maps out as a line (1) in Figure 5. The central part of the fountain is optically dense and hot (golden yellow), the fountain is moderately collimated and the column appears slightly inclined toward the right-hand side of the image (Fig. 6a). A range of temperature and optical density is observed from the core of the fountain to the margins, producing a gradation of pyroclasts and deposits. Between the center of the image and the left, an outward variation can be observed in number density and temperature in the fountain, and these variations are translated into the following deposits: (1) rootless flows resulting from high accumulation rates of hot fluid cinders on the innermost part of the cone wall, forming and flowing back down into the vent or lava pond; (2) discrete but patchy accumulations of hot plastic cinders and spatter resulting from intermediate accumulation rates, and forming local deposits of partially to completely welded spatter locally lining the middle to upper slopes of the inside of the cone; and (3) an accumulation of brittle cinders on the rim crest and outer flanks of the cinder cone due to the low number density and low temperature of the clasts in the outer zone of the fountain. On the right of Figure 6a, the inclination of the fountain causes a local rapid accumulation of coarse, hot pyroclasts which coalesce to form a rootless flow. In summary, the activity and deposits illustrated in Figure 6a map into line 1 on Figure 5, ranging from fast accumulation of hot pyroclasts in the interior of the fountain to form a lava flow/pond (point A), through rootless flows to welded spatter (point B), to accumulations of brittle cinders to form a cinder cone. This illustrates the point that at any one time a range of deposits can be formed from a single fountain.

In Figure 6b, a view of the eruption of Pu'u 'O'o on the East Rift Zone of Kilauea, both the volume flux and the gas content (as indicated by the column height; Head and Wilson, 1987) are greater than in Figure 6a, and the jet emerging from the vent is more collimated, producing a larger, optically dense fountain. Pyroclasts cool only slightly in the optically thick fountain, and fall back into the lava pond surrounding the vent at a very high accumulation rate. The lava pond is overflowing to feed a lava flow.

In another eruption episode at Pu'u 'O'o (Fig. 6c), a strong wind is distorting the distribution of small, cool clasts in the optically thin cooler parts of this fountain, and adding cinder layers downwind. Although fine cooled clasts are clearly preferentially distributed downwind, the coarse cooled clasts on the upwind side of the fountain remain, indicating that the temperature structure is not primarily determined by the wind. In summary, for a given eruption the conditions within a pyroclastic fountain can produce a range of deposits that can be directly linked to the fountain dynamic structure (Fig. 7). These residual morphologies, facies, and deposits, in turn, can be used to infer the range of conditions within the pyroclastic fountain which produced them.

So far we have considered only spatial variations within a fountain and its deposits at a given time. However, Figure 5 can also be used to predict the consequences of time variations in gas content and volume flux — either within a single eruptive episode or between successive eruptive episodes from the same vent. For example, if volume flux increases while gas content remains constant (as might happen during the early part of a protracted eruption), or if volume flux remains constant while gas content decreases (perhaps during the late stages of an eruptive event), this corresponds to trac-
ing one of a series of paths running generally from bottom left to top right in Figure 5. Of course, trends might occur in either direction for either variable, either over a short time within a single eruptive episode or over a longer time spanning a series of episodes building a polygenetic volcano. Nevertheless, all basaltic volcanoes should show detectable sequences of stratigraphic horizons in their post-eruption deposits which reflect connected pathways through Figure 5. For example, on the basis of mapping of post-eruption structures and deposits, Gutmann (1979) describes four stages of eruption and evolution of cinder cones in the Pinacate volcanic field: (1) basal flows; (2) cone-building eruptions with generally increasing clast size with time; (3) upwelling of lava and breaching of cones; and (4) terminal pyroclastic eruptions (small volume with agglutinates common). Using the procedures and relationships outlined above, we would interpret Gutmann’s stages as follows: (1) effusion of relatively low gas content magmas; (2) decrease in mass flux and increase in gas content (perhaps related to extremely low magma rise speeds and strombolian activity), and a trend in this stage toward lower gas content (increasing clast size); (3) increasing mass flux; and (4) possible terminal strombolian activity.

Conclusions

(1) The fundamental controls on deposits from pyroclastic fountains are exsolved magma gas content and volume flux.

(2) These factors determine the temperature (Fig. 3) and accumulation rate (Fig. 4) of pyroclasts on the ground. Input from the atmospheric wind speed profile is generally minor.

(3) Temperature and accumulation rate, in turn, control whether lava ponds, lava flows, welded spatter, unwelded spatter, or brittle cinders are formed (Fig. 5).

(4) A finite range of clast temperatures and accumulation rates is associated with a pyroclastic fountain even when the magma gas content and eruption rate remain constant, leading to certain specific variations in the nature of the deposits formed with radial distance from the center of the vent. Figure 5 is the basis of a systematic interpretation of actively forming fountain deposits.

(5) These relations are applicable to the analysis of ancient eruption deposits to infer (by comparison with contemporary deposits) the physical nature of the eruption (high or low effusion rate, gas-rich or gas-poor magma). If time horizons can be located in such deposits it is possible to infer the trends in eruption conditions with time.

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