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DOI: 10.1016/j.jvolgeores.2009.07.014
CONTROLS ON THE EXPLOSIVITY OF SCORIA CONE ERUPTIONS:
MAGMA SEGREGATION AT CONDUIT JUNCTIONS

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Abstract

Violent strombolian (transitional) eruptions are common in mafic arc settings and are characterized by simultaneous explosive activity from scoria cone vents and lava effusion from lateral vents. This dual activity requires magma from the feeder conduit to split into vertical and lateral branches somewhere near the base of the scoria cone. Additionally, if the flow is separated, gas and liquid (+ crystals) components of the magma may be partitioned unevenly between the two branches. Because flow separation requires bubbles to move independently of the liquid over time scales of magma ascent separation is promoted by low magma viscosities and by high magma H₂O content (i.e. sufficiently deep bubble nucleation to allow organization of the gas and liquid phases during magma ascent). Numerical modeling shows that magma and gas distribution between vertical and horizontal branches of a T-junction is controlled by the mass flow rate and the geometry of the system, as well as by magma viscosity. Specifically, we find that mass eruption rates (MER) between 10³ and 10⁵ kg/s allow the gas phase to concentrate within the central conduit, significantly increasing explosivity of the eruption. Lower MERs produce either strombolian or effusive eruption styles, while MER > 10⁵ kg/s prohibit both gas segregation and lateral magma transport, creating explosive eruptions that are
not accompanied by effusive activity. These bracketing MER constraints on eruptive transitions are consistent with field observations from recent eruptions of hydrous mafic magmas.

Keywords: Basaltic volcanism; violent strombolian eruption; gas segregation

1. **Introduction**

Scoria cone eruptions are a common and spectacular form of mafic volcanic activity that often includes either simultaneous or alternating explosions and lava effusion. Scoria cones are common in subduction zones (Michoacan-Guanajato volcanic field, Mexico; Central Cascade, USA, Auckland volcanic field, New Zealand), continental rift zones (San Francisco volcanic field, USA; Pinacate volcanic field, Mexico) and at some central volcanoes (e.g., Etna and Vesuvius, Italy; Kilauea, Mauna Loa, Mauna Kea, USA). Although most scoria cone eruptions are monogenetic (that is, single eruptive episodes), reoccurrence of vents may also occur (e.g., Etna summit craters: Behnke et al, 2006; Cerro Negro: McKnight and Williams, 1997). Historical cone-forming eruptions have had durations of days to years, with time-averaged mass eruption rates (MERs) of $10^2$ to $~10^5$ kg/s. Lava flows are typically an important component of these eruptions and can constitute a minor or major fraction of the erupted mass (e.g. 94% by weight of the magma erupted during the 1971 eruption of Etna was emitted as lava; 39% by weight of lava in the Paricutin 1943-1952 eruption; Booth and Walker, 1973, Walker 1973a, Pioli et al. 2008).

Scoria cones are constructional features that change in form through time. Early-formed cones are commonly horseshoe-shaped, constructed around the active vent and
associated lava flow. This form permits lava effusion and explosions to occur from the same vent(s). Protracted activity completes the cone by accumulation of scoria around the vent, such that explosive eruptions become localized at the cone vent while lava flows emerge from lateral vents located at the base of the cone. Gas emissions also localize at the cone vent, as explosive eruptions emit substantial amounts of gas as a free phase and scoria produced by explosive eruptions is typically more vesicular than co-erupted lava. Thus a dual-vent configuration requires both volatile segregation (to power explosive activity) and magma segregation into both vertical and lateral conduits (Krauskopf, 1948; Behnke and Neri, 2003). Finally, volatile segregation requires sufficient transit time in the conduit for bubble migration; from this perspective, we expect much more extensive segregation for volatile-rich magmas (where gas exsolution may start at > 4.5 km below the vent; Pioli et al., 2008) than in volatile-poor magmas, where most gas exsolution is very shallow (Mangan and Cashman, 1996; Edmonds and Gerlach, 2007).

Pioli et al. (2008) suggested that the synchronicity of explosive and effusive activity is a key characteristic of activity that has been termed “violent strombolian” (MacDonald, 1972) and is characterized by average mass fluxes of water-rich basalts that are intermediate between strombolian and subplinian regimes. Violent strombolian explosions are typically discontinuous and strongly pulsatory rather than steady (up to 120 explosions per minute have been described in 1943 Paricutin eruption by Foshag and González-Reina, 1956). Related effusive activity may also be discontinuous and may or may not exhibit a systematic relationship to explosive activity (Krauskopf, 1948). Violent strombolian explosions produce pyroclasts that form composite deposits that include a scoria cone, a tephra blanket, and lava flows spreading from lateral vents (e.g.,
Valentine et al., 2005; Pioli et al., 2008). This ‘mixed’ eruption style is unique to low viscosity magmas and is generally associated with high initial water contents (i.e. arc basalts, Wallace, 2005). Here we address the primary controls on mafic eruptive styles by examining the physical conditions required for this dual activity, including the structure of the feeding system and the contribution of volatile segregation to explosivity.

2. **Observational constraints on violent strombolian activity**

The geometry of magma delivery systems beneath scoria cones is best observed in older eroded monogenetic volcanoes, which reveal the syn-eruptive interplay between dike intrusion, pyroclast sedimentation, and lava accumulation in the development of the shallow magmatic conduit (Keating et al., 2008; Valentine and Keating, 2007). Feeder systems are dikes with widths of 4-12 m at depths > 100 m. Exposed shallow conduits are often complex, with multiple dikes and sills that provide evidence for extensive shallow magma storage (e.g., Johnson et al., 2008). However, field studies of eroded cones provide only crude constraints on the geometry of feeder systems during any individual eruptive phase, as the preserved structure is the integrated result of the sequence of events that comprise the volcano’s history (Keating et al. 2008).

The dynamics of violent strombolian eruptions are best revealed by observations of recent activity. Differentiation between central and lateral vents can occur within a few hours (Etna 2001 and 2002 eruptions; Behncke and Neri, 2003; Andronico et al., 2005) or may require weeks from the eruption onset (Paricutin 1943-1952; González-Reyna and Foshag, 1946). The latter example is particularly pertinent as it is the type example of a violent strombolian eruption (e.g., Macdonald, 1972) and detailed reports provide
important constraints on the development and evolution of the lateral dike system and related changes in eruption dynamics (summarized in Luhr and Simkin, 1993).

The Paricutin eruption started with the opening of a 50 m long fracture (González-Reyna and Foshag, 1946). Within a few hours, mild explosive activity had focused in the northern portion of the fracture and by the end of 24 hours, the resulting scoria cone was about 30 m high. Lava emission started on the second day from the same crater where the explosions were occurring, producing a horseshoe-shaped cone and a lava flow (Gonzalez-Reyna and Foshag, 1946). Progressive scoria accumulation around the vent gradually formed a complete cone, although it was initially subject to sector collapses related to lava effusion. The cone acquired full stability in about one month, when it was about 150 m high.

Cone stabilization coincided with the onset of the ‘cineritic phase’ of eruptive activity, that is, violent strombolian explosions that formed ash-rich columns reaching elevations of ≤ 6 km (Ordoñez, 1945) and contemporaneous emission of lava from lateral vents at the base of the cone (Fig. 2). This activity continued for several months and deposited an extensive tephra blanket composed of vesicular scoria (> ~ 60% vesicles; Pioli et al., 2008). At the same time, dense (vesicularity < 30%; Wilcox, 1954) lava was fed from vents located at the cone base or within the cone slope (Foshag and González-Reyna, 1956; Fries, 1953). Observations at the crater suggested a vent diameter of 3-8 m. Evidence of intrusion of lava within the cone during this time period is provided by pronounced bulges observed on the cone slopes before the opening of a new boca or reoccupation of an older vent. The only interruption of this pattern of activity came in late 1943, when a new vent formed about 1 km N of the volcano and caused the temporary
(2.5 months) shut off of the main cone. A new horseshoe-shaped scoria cone (the ‘Zapichu’ vent) caused the activity at the new vent to revert to mild explosions (hawaiian and strombolian) and lava effusion.

Paricutin was active for nine years (1943-1952), during which time the mass eruption rate (MER) declined (Fig. 1) while the dominant eruptive style changed from explosive (total MER $\geq 10^4$ kg/s) to mainly effusive (total MER $< 10^4$ kg/s) activity. The composition of the erupted magma also changed in the latter part of the eruption (after 1946); this compositional variation appeared at the same time in both lava and tephra products (Wilcox, 1954; McBirney, 1987; Luhr, 2001; Pioli et al., 2008; Erlund et al., in revision), demonstrating a common (shallow) source for both types of activity.

Taken together, observations of activity at Paricutin suggest that (a) the separation between the vertical conduit and lateral lava channel system occurred at a shallow depth (within or at the base of the cone), (b) the cone structure modulated the opening of new lava vents, (c) gas preferentially accumulated in the vertical conduit (giving rise to explosive activity from the central vent), (d) the mass eruption rate (MER) controlled the proportion of magma emitted by explosive vs. effusive activity, and (e) the initial formation of lateral vents increased the explosivity of eruptions occurring at the cone.

3. Numerical modeling

As outlined above, there appears to be a relationship between the development of separate vertical and lateral conduits and the onset of violent strombolian activity. To explore this relationship, we consider the geometric configuration of a T-junction with a vertical, cylindrical pipe (the central conduit) and a lateral, horizontal cylindrical branch
(the lava channel; Fig. 2). A similar geometry was used by Menand and Phillips (2007a,b) in their experimental investigation of gas segregation and accumulation in sills, but our geometry differs in allowing flow out the lateral branch.

Two-phase flow splitting through a T-junction has been studied extensively in engineering fields for water-air flows (e.g., Zetzmann, 1984; Mudde et al., 1993; Azzopardi, 1999; Conte and Azzopardi, 1999; Wang et al. 2002, Azzopardi, 2006; Yang and Azzopardi, 2007). In all cases, the distribution of liquid and gas phases is uneven when gas and liquid are characterized by different velocities, i.e. the flow is separated. This condition is satisfied for low viscosity, mafic magmas in many natural settings (e.g., Vergnoille and Jaupart, 1989; Wilson and Head, 1981). To a first approximation, the phase distribution is controlled by the relative momentum fluxes of the two phases, with the higher momentum phase concentrating in the vertical conduit. However, the mass flow distribution also depends on the geometry of the junction, the pressure drops along the two outlet conduits, and therefore the flow rates in them. These experiments also demonstrate that the most important parameters defining the flow segregation at a T-junction are conduit diameter, gas and liquid flux, and the ratio between gas and liquid volumes downstream and upstream of the junction. Experiments characterized by high liquid superficial velocities (that is, volumetric flow rate divided by the cross sectional area of the conduit) at the entry of the junction (Zetzmann, 1984) distribute gas preferentially into the lateral conduit. In contrast, experiments using lower inlet liquid flow rates preferentially distribute gas into the vertical branch (Conte, 2000).

To apply this work to volcanic activity, we use the geometry shown in the inset of Figure 2. We assume that the gas is steam with a density defined by the local pressure
and temperature, and that gas exsolution from the magma is negligible above the
junction, although gas is allowed to expand to accommodate pressure changes. We vary
magma viscosity, pressure, and channel diameter but set both outlets to atmospheric
pressure. Pressure increases inwards along the pipes to reach the same value at the
junction. Flows in the vertical and lateral outlets are adjusted until the pressures in the
two conduit branches are the same at the junction.

3.1. Governing equations

The total pressure gradient along any of the branches is the sum of the effect of
gravitational forces (G), friction loss (F) and acceleration of the fluid (A)

\[
\frac{dp_j}{dz_j} = -\frac{dp_Gj}{dz_j} - \frac{dp_Fj}{dz_j} - \frac{dp_Aj}{dz_j},
\]

where \( j \) refers to any of the three branches (1, 2, or 3). The pressure \( p_2 \) in the vertical
branch is controlled by both the gravitational and frictional components whilst the
pressure \( p_3 \) in the horizontal channel is controlled only by friction. Gas expansion effects
due to depressurization were calculated in the pipes upstream the junction assuming
equilibrium with local pressure. As it has been assumed that there is no change in the
amount of exsolved gas, the acceleration component of pressure drop was taken to be
negligible. Calculations confirmed that this was so except in the near neighbourhood of
the outlets. The calculation approach is similar to that employed by Wilson and Head
(1981) but allows the gas and liquid to have different velocities and the gas to affect the
frictional component.

Pressure changes were determined by integrating the following equations:
\[ p_2(z_2) = \int_0^{z_2} \left( \varepsilon_g \rho_g + (1 - \varepsilon_g) \rho_l \right) g + \frac{4 f_{1,2}}{D_2} \frac{\rho_l u_{ls}^2}{2} \left[ 1 + \frac{C}{X} + \frac{1}{X^2} \right] \, dz, \]  

and \[ (2) \]

\[ p_3(z_3) = \int_0^{z_3} \left( \frac{4 f_{1,3}}{D_3} \frac{\rho_u u_{uls}^2}{2} \left[ 1 + \frac{C}{X} + \frac{1}{X^2} \right] \right) \, dz, \]  

with equation (2) representing pressure changes in the vertical branch (including both gravitational and frictional forces) and equation (3) representing pressure changes in the horizontal branch (which includes only the frictional force).

\[ \text{3.2. Calculating the gravitational component} \]

The gravitational component includes the void fraction \( \varepsilon_g \), which is calculated using a drift flux approach to allow for different velocities of gas and liquid (Wallis, 1969):

\[ \varepsilon_g = \frac{u_{ls}}{C_0 (u_{ls} + u_{gs}) + v_{gd}} \]  

(4)

In these equations \( u_{ls} \) and \( u_{gs} \) are the surficial velocities of liquid and gas, respectively, and they represent the velocities they would have if they were flowing alone in the channel. \( v_{gd} \) is termed the gas drift velocity, that is the relative velocity of the gas phase, and for bubble flows is given by:

\[ v_{gd} = K_1 \left( \frac{g \, (\rho_l - \rho_g)}{\rho_l} \right)^{0.25}, \]  

(5)

with \( K_1 = 1.53 \) (Harmathy, 1960), \( \rho \) is the phase density and \( \sigma \) is the liquid surface tension.

The constant \( C_0 \) in equation (3) is called the distribution factor (Zuber and Findlay, 1965) and compensates for the effects of velocity profiles in the gas and liquid.
flows (that is, non-uniform distribution of gas in the flow); its value depends on whether
the flow of the gas and liquid is laminar or turbulent. Flow regime, in turn, is described
using the Reynolds (Re) number, a dimensionless parameter that relates inertial and
viscous forces:

\[ Re = \frac{\rho u_j D_j}{\eta_i} \]  

(6)

We calculate Re separately for the gas and liquid phases using appropriate values for
density (\(\rho\)), viscosity (\(\eta\)), and velocity (\(u\)). In cylindrical pipes, transition from laminar to
turbulent flow is expected at \(Re \sim 4000\) (Coulson et al., 1996). In our simulations \(Re <\)
2000 for the liquid and \(Re > 2000\) for the gas; we follow Zuber and Findlay (1965) in
using \(C_0=1.2\) for this situation.

3.3. Calculating friction

The friction factor \(f\) in equations (2) and (3) is a dimensionless number that
represents the ratio between friction forces and forces normal to the pipe walls and is
calculated as \(f = \frac{16}{Re}\) for \(Re<2000\) and \(f = \frac{0.079}{Re^{0.25}}\) for \(Re>2000\). The frictional term
describes the frictional component of pressure drop along the vertical conduit (with
diameter \(D_2\)) and horizontal channel (with diameter \(D_3\)). The term in the square brackets
is a correction factor that incorporates the effect of the gas phase on the frictional
pressure drop (Azzopardi and Hills, 2003). It is based on the dimensionless Martinelli
parameter \(X\) (Lockhart and Martinelli, 1949), the square root of the ratio of frictional
pressure gradients for the liquid and gas, calculated from the mass flow rates, densities
and total channel cross sectional area:

\[ X^2 = \frac{\left( \frac{dp_v}{dz} \right)_L}{\left( \frac{dp_v}{dz} \right)_g}. \]  \hspace{1cm} (7)

The constant \( C \) in equations (2) and (3) is a correlating parameter depending on the regime of each phase. It takes the value of 20 when both phases are turbulent, 5 if they are both flowing in laminar regime, 10 when the liquid phase is turbulent and the gas phase is laminar, 12 in the opposite condition (Chisholm, 1967).

3.4. Conservation of mass

Conservation of mass is satisfied when:

\[ M_{l1} = M_{l2} + M_{l3}, \]  \hspace{1cm} (8)
\[ M_{g1} = M_{g2} + M_{g3}. \]  \hspace{1cm} (9)

The effect of redistribution of gas and liquid phases at the junction is given by an empirical equation of Conte (2000), which fits experimental results of mass redistribution in T junctions from Conte (2000) and Zetzmann (1984)

\[ L' = \frac{\dot{M}_{l3}}{\dot{M}_{l1}} = \frac{23.5}{\rho_g u_{l2}} \left( \frac{\dot{M}_{g3}}{\dot{M}_{g1}} \right) + 0.5 \left( \frac{\dot{M}_{g3}}{\dot{M}_{g1}} \right)^2. \]  \hspace{1cm} (10)

The liquid flow rate in the side branch, \( \dot{M}_{l3} \), is chosen at the start of each simulation. Equation (8) then gives the liquid flow rate in the vertical channel, \( \dot{M}_{l2} \). The gas flow in the side branch, \( \dot{M}_{g3} \), is obtained from equation (9) and that in the vertical channel, \( \dot{M}_{g2} \), using equation (10). The pressure drops in the two channels are then calculated using
equations (2) and (3) and $\dot{M}_{i3}$ is adjusted until the two pressure drops are equal.

### 3.5. Model limitations and applicability

The model conservation equations have general validity, however, calculation of the gravitational pressure drop requires calculation of the drift velocity, which depends on the flow regime. In this model calculations in equation (5) were made assuming a bubbly flow regime. For slug flow it is usual to express the drift velocity in terms of the Froude number $Fr$ (White and Beardmore, 1962), the ratio between of inertial to buoyancy forces:

$$Fr = \frac{u_i^2}{gD_j}.$$  

(11)

By substitution,

$$v_{gd} = Fr \sqrt{gD_j}.$$  

(12)

$Fr$ is expected to vary between 0.1 and 0.345 (Seyfried and Freundt, 2000). However, examination of the relative values of the terms in equation (4) shows that the first term in the denominator is much larger than the second so the either equation (5) or (12) will give very similar values of void fraction when inserted in equation (4). For this reason, even if in our calculations we simulated bubbly flow regimes, the results can be extended with good approximation to slug flows.

To ensure applicability and limitations of empirical parameters derived from experiments on air-water systems, we compare the volcanic and experimental systems using appropriate dimensionless parameters to define flow regimes. Relevant
dimensionless parameters for bubbly flows are Eotvös number $Eo$, that is the ratio between buoyancy and surface tension forces $Eo = \frac{\rho g D^2}{\sigma}$, Morton number $Mo$, relating viscous to surface forces $Mo = \frac{g \eta^4}{\rho^4 \sigma^3}$, and Reynolds number $Re$ (Grace, 1973; Kulkarni and Joshi, 2005). In basaltic magma flows, $Re < 10^3$, $10^5 < Eo < 10^7$, and $10^5 < Mo < 10^{10}$ (Seyfried and Freundt, 2000). $Fr$ number is not expected to vary significantly respect within the range of simulation conditions (Seyfried and Freundt, 2000). For comparison, experiments of Zetzmann (1984) and Conte (2000) have $10^2 < Eo < 10^3$; $10^{-10} < Mo < 10^{-11}$, and $10^3 < Re < 10^5$. The differences between the natural and experimental conditions are thus large, which will affect both bubble shape and velocity. In particular, gas velocity in our simulations will be underestimated by about one order of magnitude because of the high $Mo$ anticipated in volcanic systems (e.g., Rodrigue, 2004). This limitation will affect both pressure calculations and mass distributions, leading to an overestimation of the amount of gas that is directed into the lateral branch.

4. Results

4.1. Mass distribution

To model basaltic eruptions, we solve the equations for $\rho_l=2800$ kg/m$^3$, $\sigma=0.4$ N/m calculate gas density at $T=1442$ K; we vary the vertical and lateral conduit diameters, vertical conduit length, gas and liquid mass fluxes, and liquid viscosity. In all the cases the length of the lateral conduit was taken to be $\sqrt{3}$ times the height of the vertical conduit above the junction, to reproduce the stable geometry of a scoria cone. Most calculations used a lateral branch diameter of 2 m, as solutions of the equation system were possible.
for smaller diameters only at the lowest flow rates considered. This value is in agreement with observed dikes and conduits at depths >100m (Keating et al., 2008).

In all of the simulations, the liquid and gas phases redistribute in the two branches upstream of the junction. At low mass flux, the mixture is preferentially drained through the horizontal branch until a saturation value, above which further mass flux increases are accommodated in the vertical conduit (Fig. 3a). Mass distribution is controlled by the relative diameter of the vertical and lateral branches and the height of the vertical branch (which controls the pressure at the T-junction). As the diameter of the lateral branch increases relative to that of the vertical branch, the vertical MER decreases and the lateral MER increases (Fig. 3b). Increasing length of the vertical branch, (which simulates increasing the height of the cone), increases the pressure at the junction diminishing the effect of the diameter increase (Fig. 3b), although pressure is not very sensitive to small variations of the side channel diameter (Fig. 3c).

Magma viscosity also affects partitioning of gas and liquid within the system. In particular, increasing the magma viscosity dramatically decreases liquid drainage through the lateral system, such that an order of magnitude increase in viscosity forces the mixture to emerge vertically for a range of MER. This is not surprising, as the lateral pressure drop is directly proportional to viscosity at low Reynolds numbers, as shown in section 3.3. In contrast, the vertical pressure drop is more strongly controlled by the gravitational component than frictional, thus the total pressure drop is not as sensitive to an increase in viscosity.

4.2. *Phase distribution*
Gas distribution between the vertical and lateral branches is controlled by the total MER, the geometry of the system, and the pressure at the junction. Gas is generally partitioned into the vertical conduit except when the junction pressure is high and/or the lateral channel diameter is large. Gas accumulates in the lateral branch when the gas volume flux is low with respect to the magma volume flux. This condition can be achieved either through lengthening the vertical branch (increasing junction pressure; Fig. 4a) or by extensive pre-eruptive magma degassing. Under these conditions, the mass of gas emerging with the lateral flow increases with the lateral conduit diameter (Fig. 4a), The distribution of gas between the vertical and lateral branches, in turn, affects the energetics of eruptions from the main vent, the lateral transfer of gas (via the magma) through the cone, and the consequent vesicularity of the erupted lava.

The role of total MER in gas segregation is shown in Figures 4b and 4c. At low MER, the percentage of gas emerging with the lateral flow increases with increasing total MER and gas flux is larger in the lateral channel than the vertical conduit. In our simulations, when flow rate exceeds $10^3$ kg/s, pressure balance at the junction can be achieved only if the diameter of the lateral branch is decreased (from 2 to 1.35 m at the highest flow rates). Under these conditions, the gas flux in the lateral channel remains constant and the percentage of gas in the lateral channel decreases as total flow rate increases. The same result could be obtained with a larger diameter if significant wall roughness were assumed.

5. Discussion

Modeling results indicate that flow splitting at a dike junction has the potential to
generate an unequal distribution of the bulk flow between the vertical and lateral conduits as well as a redistribution of liquid and gas phases. Variable distribution of both the total mass flux and the gas and liquid fluxes between the central and lateral vents can explain both temporal variations in eruptive style and the simultaneous explosive and effusive activity that is commonly observed during scoria cone eruptions. Our simulations suggest that partitioning of magma between the vertical conduit and lateral channel is controlled primarily by the total MER and geometry of the junction. Numerical modeling also suggests that eruptions should be dominated by lateral vent activity when MER < $10^3$ kg/s, above which the relative proportion of magma erupted from the central conduit increases rapidly until the flow through the lateral conduit is completely suppressed at MER > $10^5$ kg/s (Fig. 5).

Modest variations in the diameter of the lateral channel affect not only the redistribution of the magmatic mixture (Fig. 5) but can also change the segregation of gas between the vertical and lateral branches, thus indicating that flow spitting between central and lateral conduits has important implications for eruption dynamics. In general, the higher momentum phase concentrates in the vertical branch and the lower momentum phase in the lateral branch. Thus extensive phase segregation can occur only when the flow is separated (i.e., gas bubbles are moving independently of the liquid), because this is the only condition where the phases have different momentum. An additional effect of gas segregation is enhancement of explosivity at the central vent.

Gas preferentially accumulates in the lateral branch only when the gas volume flux is low with respect to the magma volume flux (i.e. the mixture has low vesicularity). This condition can be achieved either by increasing the depth of the T–junction within the
cone or by pre-eruptive magma degassing. The former situation may serve to limit the maximum height of scoria cones. Another factor that may affect gas accumulation in the lateral branch is concentration of bubbles in the center of the flow (e.g., Lucas et al., 2005), as magma is preferentially drained into the lateral branch from the side of the conduit.

5.1. Application of simulation results to activity at Paricutin

Our primary goal was to explain the observed correlation between mass eruption rate and the relative proportion of mass erupted from vertical (or lateral) vents (Fig. 1). Our model results for variations in vertical and lateral eruption rates (Fig. 6) match observed rates for Paricutin (Fig. 1) when the vertical and lateral conduit branches have diameters of 5 and 2 m, respectively, and the cone height is 500 m. These parameter values seem reasonable given the substantial cone height (300-400 m) and estimated vent diameters (3-8 m in the cone; 1-3 m for the lateral bocas; Foshag and González-Reyna, 1956) observed during the cineritic phases of Paricutin’s eruption. A magma viscosity of 300 Pa s is also reasonable given a bulk melt composition of 54-55 wt% SiO$_2$, H$_2$O contents of ≤ 4 wt% (Pioli et al., 2008), and temperature of 1100˚C (Luhr, 2001).

While the results of our simulation do not uniquely constrain the geometry of Paricutin’s shallow feeder system, the sensitivity of the simulation to variations in both lateral channel dimension and magma viscosity does not allow much latitude in these parameters. Moreover, our simulations suggest that the lateral branch should saturate at $10^3 < \text{MER} < 10^4$ kg/s given magma properties and channel geometries appropriate for the 1943 eruptive activity at Paricutin; higher MER require partitioning into the vertical branch.
A second goal was to test the hypothesis that the onset of cineritic activity at Paricutin can be explained by development of a junction within (or just below) the cone that feeds simultaneous eruptions from the scoria cone vent and effusive vents at the base of the cone. By definition, there is no segregation of the flow when the cone is incomplete. Our simulations show that at MERs appropriate for early phases of the Paricutin eruption, completing the cone would have promoted extensive gas segregation into the vertical branch.

Our results also allow us to speculate on the nature of the Zapichu episode (that is, the time period when activity shifted to a lateral vent). Krauskopf (1948) suggested that the lateral vent was connected to the main feeder conduit at a depth of 600-700 m below the one. Our simulations would suggest that depth, which would have doubled the junction pressure, which would have caused the gas to segregate strongly into the lateral dike. This predictions corresponds with observations, as explosive activity at the central vent ceased at this time, while pyroclasts emitted from the Zapichu vent were described as unusually vesicular. Additionally, strombolian to Hawaiian activity at the new Zapichu cone (limited gas segregation) is consistent with the horseshoe shape of the new vent structure.

5.2. A general mechanism?

A compilation of historic basaltic eruptions shows that simultaneous tephra and lava production occurs over a limited range of mass eruption rates (MER= $10^3$-$10^5$ kg/s; Table 1). Here we have included only eruptions of water-rich (subduction zone) basalts, where volatile segregation can commence within feeder conduits (e.g., Pioli et al., 2008). We measure the relative importance of explosive activity (that is, gas-enriched magma that is
seggregated into the vertical conduit) by determining the ratio between the mass of the
tephra blanket and the entire eruptive mass (e.g., tephra blanket, scoria cone, and lava
flows). As illustrated in Figure 7, the results show striking similarities with numerical
modeling results: eruptions with MER <10$^3$ kg/s do not form tephra blankets; between
10$^3$ and 10$^5$ kg/s there is a positive relationship between MER and blanket mass;
MER$\geq$10$^5$ creates purely explosive eruptions (subplinian to Plinian).

The transitional (violent strombolian) regime is characterized by explosive activity
(with eruption columns to $\leq$ ~ 6 km height) accompanied by lava effusion from the base
of the cone (e.g., Krauskopf, 1948). Additionally, eruptions within this regime show a
direct correlation between explosivity, as defined by tephra production, and magma flux
(Fig. 7). Our modeling shows that simultaneous eruption of tephra from the cone and
lava flows from lateral vents requires segregation of bubbly magma into a gas-rich
mixture that ascends through the central conduit and gas-poor lava flowing in the lateral
system. This gas segregation must occur at a shallow depth (within or just below the
scoria cone), as high junction pressures serve to force the flow into the horizontal, rather
than the vertical, branch (e.g., the Zapichu episode). Segregation is also limited to
volatile-rich low viscosity magmas, conditions that promote separated flow of the gas and
liquid phases. We therefore conclude that the dual activity that characterizes violent
strombolian activity is unique to mafic eruptions of sufficient duration to construct
complete scoria cones and with 10$^3$<MER<10$^5$ kg/s.

When magma flow exceeds 10$^5$ kg/s, gas segregation is no longer possible, flow into
the lateral conduit ceases, and we would expect eruptive activity to take the form of
sustained columns (subplinian to Plinian activity). This prediction is consistent with
estimated MER for a paroxysmal eruption of Stromboli in 2003 (MER > 10^5 kg/s; Rosi et al., 2006), a subplinian eruption of Shishaldin volcano in 1999 (MER = 2.5 \times 10^6 kg/s; Stelling et al., 2002) and for Plinian eruptions of Mt. Etna in 122 BC (Coltelli et al., 1998) and Tarawera 1886 (Houghton et al., 2004), which had MERs of 5-10 \times 10^7 kg/s.

At eruption rates below 10^3 kg/s, degassing dominates, producing either lava effusion and/or mild explosive activity. Observations at Stromboli suggest that magma fluxes > ~ 400 kg/s produce lava flows, while MER < ~ 100 kg/s reflect an effectively static magma column where magma is ejected by bubble bursting at the surface at a rate controlled by the gas flux (e.g., Chadwick et al., 2008). Low MER will also promote progressive closure of the lateral channel because of the decrease in channel diameters required to achieve pressure balance, as described by Ripepe et al. (2005) for the 2002-2003 eruptive crisis at Stromboli. However, complete conduit closure cannot be modeled with our calculations because they do not take into account viscoelastic properties of the wall rocks.

5.3. The role of viscosity

Our simulations also provide insight into the role that magma viscosity might play in modulating eruption style. Increasing the viscosity of the magma liquid drainage through the lateral system (Fig. 3c). Even a modest increase in viscosity (from 300 to 3000 Pa s) has a significant impact on flow splitting, a result that is consistent with the increasing time scale required for gas phase separation in viscous fluids. Thus we would expect that lateral flow of magma would be absent in eruptions of high viscosity magmas. Observations of recent eruptive activity confirm this. In these systems, high MERs (\geq 10^6 kg/s) produce subplinian to Plinian eruptions while low MERs (< 10^4 kg/s) produce
viscous flows and domes (e.g., Scandone and Malone, 1985; Scandone et al. 2007).

However, transitional activity in silicic systems (that is, activity produced by $10^4 < $MER
< $10^6$) differs from that of mafic systems in that explosive and effusive activity occur
sequentially rather than simultaneously, often with Vulcanian explosions followed by
dome effusion (e.g. Druitt et al., 2002; Wright et al, 2006). In these systems, the gas
segregation required to power the explosive events accumulates between, rather than
during, eruptive episodes.

6. Conclusions

Taken together, our results and the field observations suggest that shallow gas
segregation is particularly important for transitional eruptions of water-rich arc basalts,
which are characterized by high gas fluxes and separated flow conditions. In particular,
Figure 7 illustrates a dramatic increase in explosivity as MER changes from $10^3$ to $10^5$
kg/s, as documented by both the formation of convective columns capable of depositing
tephra blankets and by an increasing proportion of tephra with increased MER. For these
eruptions, explosivity can be strongly increased by shallow segregation of gas into
vertical conduits within early-formed scoria cones. This configuration, which is
associated with high gas fluxes and relatively low magma viscosity, causes efficient
redistribution of liquid and gas phases above (upstream of) the junction. Our simulations
predict that gas will concentrate increasingly in the vertical upper conduit as the total
MER exceeds $\sim 10^4$ kg/s, as shown in Fig. 4b, generating an abrupt increase of
explosivity with respect to ‘normal’ strombolian regimes. Numerical modeling indicates
that the segregation is more efficient for lower viscosity magmas, in agreement with
experimental results of Menand and Phillips (2007a,b).

Gas segregation is most efficient when the diameter of the lateral dike is small and the magma flux is high. In contrast, gas will be preferentially concentrated in large lateral conduits, particularly when junction pressures are high. Liquid is also segregated into large lateral dikes, suggesting that widening of lateral dikes through time should both increase the mass flux of lava from lateral vent and increase the lava vesicularity. Increasing viscosity, which increases the pressure drop across the lateral conduit, also enhances vertical magma flow. Together, temporal changes in scoria cone height (which controls junction formation and pressure), mass eruption rate (which typically diminishes with time) and magma viscosity (which changes with composition and crystallinity) can explain observed changes in the eruption dynamics of violent strombolian eruptions. More generally, we demonstrate that shallow gas segregation processes affect the intensity and importance of both explosive and effusive components of mafic volcanism.

Our results cannot be extended to fissure eruptions, where spatial differentiation of vents is likely related to the dynamics of magma rise within the dike and large MER (>10^3 kg/s, Keszthelyi et al., 2006) can be achieved without significant explosive dynamics. They are also not appropriate for volatile-poor Hawaiian eruptions, where vesiculation is sufficiently shallow that separated flow is unlikely except at very low effusion rates (e.g., Mangan and Cashman, 1996; Gerlach and Edmonds, 2007). Finally, this numerical model does not attempt to describe the fragmentation of magma that is expected to occur at shallow depths within the scoria cone, as required by the eruptive dynamics, the extensive tephra deposits, and the textural and petrographic characteristics of the Paricutin tephra (Erlund et al., 2009).
ACKNOWLEDGMENTS

L.P was supported by NSF EAR0510493 (to KVC) and Swiss National Science Foundation FNSFN 200021-122268 projects. The authors wish to thank M. Ripepe and M. James for careful reviews and L. Wilson for editorial handling of the manuscript. We would also like to acknowledge our debt to Jim Luhr, who provided us with strong support for this project, and to both Jim Luhr and Tom Simkin for their wonderful book on Paricutin. We will miss them both.
APPENDIX

List of symbols

\( D = \) diameter

\( f = \) friction factor

\( g = \) gravitational acceleration

\( p = \) pressure

\( u = \) velocity

\( u_s = \) superficial velocity

\( v_{gd} = \) gas drift velocity

\( z = \) vertical length

\( \sigma = \) liquid surface tension

\( \varepsilon_g = \) void fraction

\( \eta = \) viscosity

\( \rho = \) density

\( Eo = \) Eotvos number

\( Fr = \) Froude number

\( Mo = \) Morton number

\( Re = \) Reynolds number

List of subscripts

1, 2, 3 refer to branches 1, 2, 3 of the junction, as numbered in fig. 2

l, g refer to liquid and gas, respectively

i refers to any of the phases considered (liquid or gas)
\( j \) refers to any of the branches of the junction (1,2,3)
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Figure caption

Figure 1. a) Year average effusive MER vs. Explosive MER for the Paricutin eruption. Explosive MER was calculated using year cone and tephra blanket erupted volumes, effusive MER calculated after year erupted lava volumes as calculated in Pioli et al. (2008).

Figure 2. Sketch of scoria cone and lava channel. Inset shows the simplified geometry assumed for numerical modeling.

Figure 3. a) Effect of vertical channel diameter (indicated by the numbers in the inset) in flow redistribution upstream the junction. \( D_1/D_2 = 2.5 - 3.5 \); inset shows diameters of vertical branch for the three simulations. b) Effect of side branch diameter and main channel height on vertical and lateral mass flow rates emerging from the two exits. Black lines refer to the main channel flow, red lines are for the side branch flow. Total flow rate = \( 4 \times 10^4 \) kg/s. Vertical channel height: continuous line = 100 m; thick dashed line = 350 m; thin dashed line = 500 m. c) Effect of side branch diameter and main channel height on pressure calculated that the junction point. Total flow rate = \( 4 \times 10^4 \) kg/s. Vertical channel height: continuous line = 100 m; thick dashed line = 350 m; thin dashed line = 500 m d) Relationship between vertical and lateral mass flow rate. Height of main channel = 500 m. \( D_2 = 5 \) m, \( D_3 = 1.5 \) m; \( \eta_i \): continuous line= 300 Pa s; dashed line = 3000 Pa s.

Figure 4. a) Effect of lateral dike diameter and height of main channel on percentage of gas emerging from the side branch, calculated with respect total gas flux. Total flow rate = \( 4 \times 10^4 \) kg/s b); b) Effect of total flow rate and height of main channel on percentage of gas emerging from the side branch respect with the total gas flux. Vertical channel height: continuous line = 100 m; thick dashed line= 350 m; thin dashed line= 500 m.

Figure 5. Relative proportion of mass flowing through the junction into the vertical conduit vs. total mass flux rate. \( \eta_i = 300 \) Pa s Thin line: \( D_2 = 4 \) m, thick line: \( D_2 = 7 \) m.

Figure 6. Effects of magma splitting at a conduit junction when \( D_2 = 5 \) m, \( D_3 = 1.5 \) m, \( \eta_i = 300 \) Pa s, cone height =500 m, compared with year average mass eruption rates of lava and tephra at Paricutin volcano, as shown in Fig. 1.

Figure 7. a) Average MER vs. mass fraction of tephra blanket relative to total mass of erupted material of explosive eruptions of water-rich basalts. Violent strombolian
eruptions (central area) are characterized by variable erupted tephra, and MER between $10^4$ to $10^5$ kg/s, whereas purely explosive, subplinian to plinian eruption (higher MER) are characterized by very little or no lava emission. Smaller MER eruptions (strombolian to effusive) do not form substantial tephra blanket and have lower MER. Data listed in Table 1.

Table caption
Table 1. Characteristics and references of basaltic eruptions plotted in figure 7. Asterisks indicate Mass Discharge Rate data obtained from deposit characteristics.
<table>
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<th>Eruption</th>
<th>Duration (days)</th>
<th>Average MER (Kg/s)</th>
<th>Blanket/ tot mass</th>
<th>Ref.</th>
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