



ELSEVIER

Available online at www.sciencedirect.comJournal of volcanology
and geothermal research

Journal of Volcanology and Geothermal Research xx (2007) xxx – xxx

www.elsevier.com/locate/jvolgeores

The gas content and buoyancy of strombolian ash plumes

Matthew Patrick *

Department of Geological and Mining Engineering and Sciences, Michigan Technological University,

1400 Townsend Drive, Houghton, Michigan, 49931, United States

Hawaii Institute of Geophysics and Planetology, School of Ocean and Earth Science Technology, University of Hawaii Manoa,

1680 East-West Road, Honolulu, Hawaii 96822, United States

Received 29 January 2007; received in revised form 27 May 2007; accepted 5 June 2007

Abstract

Plinian plumes erupt with a bulk density greater than that of air, and depend upon air entrainment during their gas-thrust phase to become buoyant; if entrainment is insufficient, the column collapses into a potentially deadly pyroclastic flow. This study shows that strombolian ash plumes can be erupted in an initially buoyant state due to their extremely high initial gas content, and in such cases are thus impervious to column collapse. The high gas content is a consequence of decoupled gas rise in the conduit, in which particles are ultimately incidental. The relations between conduit gas flow, eruption style and plume density are explored here for strombolian scenarios and contrasted with conventional wisdom derived from plinian eruptions. Considering the inherent relation between gas content and initial plume density together with detailed measurements of plume velocities can help unravel ambiguities surrounding conduit processes, eruption styles and hazards at poorly understood volcanoes. Analysis of plume dynamics at Santiaguito volcano, Guatemala adds further support for a model involving decoupled gas rise in the conduit.

© 2007 Published by Elsevier B.V.

Keywords: ash plume dynamics; strombolian eruption; buoyancy; volcanic conduit processes

1. Introduction

Conventional wisdom holds that explosive eruption plumes exit the vent with a density greater than that of air, and that air entrainment is required for a volcanic plume to become buoyant (Sparks and Wilson, 1976; Woods, 1995). This study explores the reasons why this idea is ‘plinian-centric’ and appears to be inaccurate for some strombolian ash plumes. The

distinction between plinian and strombolian plumes is studied here in the context of gas content, parameterized by the gas mass fraction. Understanding the relation between the gas mass fraction and initial bulk density of a plume can bear insights on the nature of gas flow in the conduit, while offering potential insight on eruption processes and pyroclastic flow hazards. Stromboli volcano, Italy, is focused on here due to the large amount of available imaging data and the relatively well-understood eruption mechanism in place, but the analysis may also be useful for poorly understood volcanoes. This short paper is meant to open a discussion on these topics and invite feedback on the ideas presented here.

* Department of Geological and Mining Engineering and Sciences, Michigan Technological University, 1400 Townsend Drive, Houghton, Michigan, 49931, United States.

E-mail address: mpatrick@mtu.edu.

2. The gas mass fraction

The gas mass fraction (n) is defined as the ratio of volcanic gas mass to total erupted mass, where the total erupted mass is the sum of masses of volcanic gas and lava:

$$n = \frac{m_{\text{gas}}}{m_{\text{gas}} + m_{\text{lava}}} \quad (1)$$

In an explosive eruption this ratio considers the volcanic gas and particles, and the particles may comprise sizes ranging from coarse ballistic ejecta to fine ash. Two simplified versions of the gas mass fraction are used here: the overall gas mass fraction (n_{overall}) which involves erupted gas and all particles, and the plume gas mass fraction (n_{plume}) which considers erupted gas and only those particles which do not rapidly decouple from the gas phase. Thus, this study concerns the gas mass fraction exiting the vent, and does not consider longer-term processes controlling gas mass fraction such as sedimentation.

The gas mass fraction has several implications for understanding eruptive behavior. First, the ratio can indicate coupled versus decoupled gas rise in the conduit. In plinian eruptions, the overall gas mass fraction (n_{overall}) is usually <0.05 , because the gas and parent magma stay closely coupled during ascent in the conduit (due to high magma viscosities) and the erupted gas mass fraction essentially reflects the original gas content of the magma (generally $<5\%$ by mass). Larger gas mass fractions (>0.05), like those found in strombolian eruptions and described below, indicate gas concentrations exceeding those typically found in magma, thereby suggesting that gas has decoupled (segregated) at depth from its parent magma and concentrated in some manner before eruption.

The gas mass fraction also provides insight on plume behavior, as n_{plume} controls the bulk density, and therefore, the susceptibility of the plume to collapse and produce pyroclastic flows. Fig. 1A shows the relation of n_{plume} to bulk density for two scenarios. In the first scenario, the gas and particles begin at magmatic temperature ($1000\text{ }^{\circ}\text{C}$). This situation would be expected for coupled gas rise in the conduit (e.g. plinian), or for decoupled gas rise (e.g. strombolian) where the fine particles are sourced from hot, fluid magma. In the second scenario the gas is at magmatic temperature ($1000\text{ }^{\circ}\text{C}$), but the particles are at ambient ($20\text{ }^{\circ}\text{C}$), reflecting the extreme case of a gas explosion entraining all particles from, say, clastic material clogging the vent (Patrick et al., 2007). For the first scenario, values of n_{plume} greater than 0.14 result in

initial bulk densities which are less than that of air ($\sim 1\text{ kg m}^{-3}$), and in the second scenario n_{plume} must be >0.26 to be initially less dense than air. Because plinian eruptions have gas mass fractions less than 0.05 (and n_{overall} can be taken as a reasonable approximation for n_{plume} for plinian scenarios), plinian plumes have initial bulk densities of $>3.5\text{ kg m}^{-3}$. Thus plinian plumes will collapse if air entrainment is insufficient.

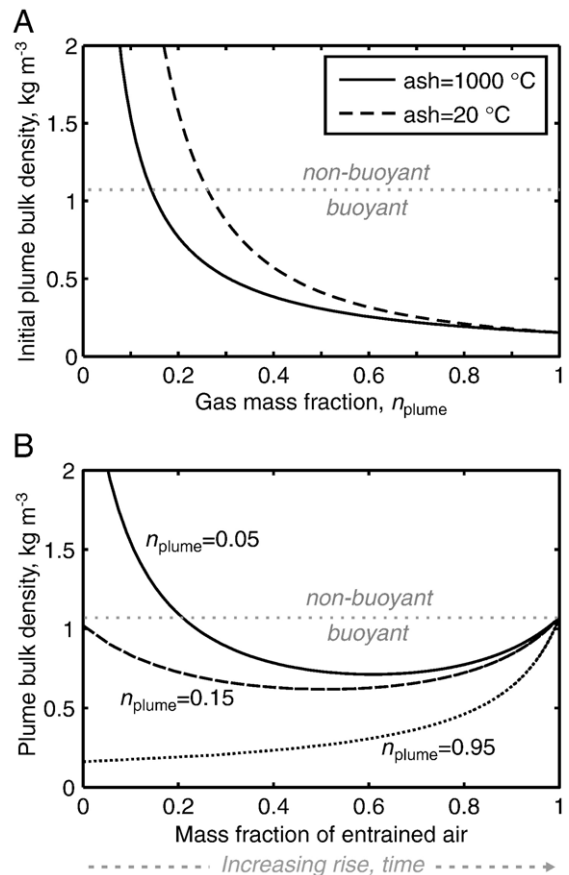


Fig. 1. A) Relation of gas mass fraction to initial bulk plume density (i.e. prior to entrainment of air). The solid line shows results for the scenario of gas and ash at $1000\text{ }^{\circ}\text{C}$, resulting in a critical n_{plume} of 0.14 for initial buoyancy. The dashed line shows results for gas at $1000\text{ }^{\circ}\text{C}$ and ash at $20\text{ }^{\circ}\text{C}$ (e.g. cold entrained particles), and a critical n_{plume} of 0.26 for initial buoyancy. Note that the $20\text{ }^{\circ}\text{C}$ ash scenario uses the simplifying assumption of instantaneous thermal equilibrium, which provides an upper limit in terms of critical gas mass fraction for this scenario. Also note that assuming a magmatic temperature of $800\text{ }^{\circ}\text{C}$ results in only a minor change in critical gas mass fractions for the two scenarios (0.17 and 0.28, respectively). B) Relation of entrained air mass to bulk density of a small plume, for several plume gas mass fractions (assuming gas and ash at a magmatic temperature of $1000\text{ }^{\circ}\text{C}$). Air content increases as the plume rises, and plume density approaches that of ambient as air content dominates. Note this plot assumes a uniform atmosphere, which is reasonable for the small (hundred meter-scale) plumes in this study.

3. The gas mass fraction in strombolian eruptions

Chouet et al. (1974) and Blackburn et al. (1976) published pioneering studies on strombolian eruptions and each independently estimated values for the gas mass fraction (0.71–0.94 and 0.11–0.38, respectively) which were significantly higher than the gas content of the magma (a few weight percent). This was interpreted as evidence that gas decouples at some depth at Stromboli, providing support for the theory that strombolian eruptions are caused by the bursting of large gas slugs.

Patrick et al. (2007) noted that, based upon their eruption descriptions and photos, the Chouet et al. and Blackburn et al. studies analyzed two distinct strombolian eruption styles (Types 1 and 2, as described in Patrick et al.). Type 1 eruptions, like those apparently studied by Chouet et al. (1974), consist of coarse ballistic scoria (cm/dm-scale) and a relatively ash-free gas plume —

consistent with the common perception of strombolian eruptions as fountains of incandescent scoria produced by a gas slug bursting in fluid magma. Type 2 eruptions (Fig. 2), like those apparently studied by Blackburn et al. (1976), produce an ash plume, with or without additional ballistic scoria. Several studies have shown Type 2 behavior to be caused by insliding of loose clastic material into the vent (e.g. Murata et al., 1966; Booth and Walker, 1973), while recent studies have also provided evidence to suggest that ash-rich strombolian behavior can be due to rheological changes in the uppermost magma column (e.g. Taddeucci et al., 2004; Lautze and Houghton, 2005). Ripepe et al. (2005) has shown the stability of the bubble bursting mechanism at Stromboli, persisting even throughout the 2002–2003 effusive phase and crater collapse. I assume here that the normal bubble bursting mechanism is responsible for both types (1+2) of strombolian activity, but in Type 2 cases is modified by either backfill or rheological changes. Because the particles ejected in any strombolian bubble bursting explosion are simply bits of lava accelerated by the gas burst and do not comprise the parent magma for the vast majority of gas ejected, the particles — regardless of Type 1 or 2 style, and regardless of Type 2 origins — are ultimately incidental.

The distinction between Type 1 and 2 styles indicates that the gas mass fraction studied by Chouet et al. (1974) for Type 1 eruptions reflects the relative amount of gas and ballistic particles (n_{overall}), whereas the value estimated by Blackburn et al. (1976) for Type 2 eruptions reflects the relative amount of gas and ash in the plume (n_{plume}). Because the ramifications on ash plume dynamics are of primary interest in this study, the gas mass fraction in Type 2 plumes (n_{plume}) is the focus of this study.

Rose et al. (1980) followed these studies with in situ analyses of small ash-rich eruption plumes at Fuego volcano in February 1978, which were also studied by Wilson and Self (1980). The plumes had initial velocities of 5 to 30 m s⁻¹, and rose to heights of several hundred meters — similar in scale and intensity to strombolian eruptions. Rose et al. combined direct sampling of particles from an airplane with gas chromatography and inferred the initial gas mass fraction for the plume (n_{plume}) to be between 0.67 and 0.95. These values were remarkably similar to those of Chouet et al. (1974), leading Rose et al. to speculate that the plumes reflected a kind of ash-rich strombolian style. Although very similar, the Rose et al. (1980) and Chouet et al. (1974) results do not necessarily reinforce one another, again, because they pertain to Type 1 (n_{overall}) and 2 (n_{plume}) styles, respectively — unlike plinian scenarios, it is not reasonable to generally

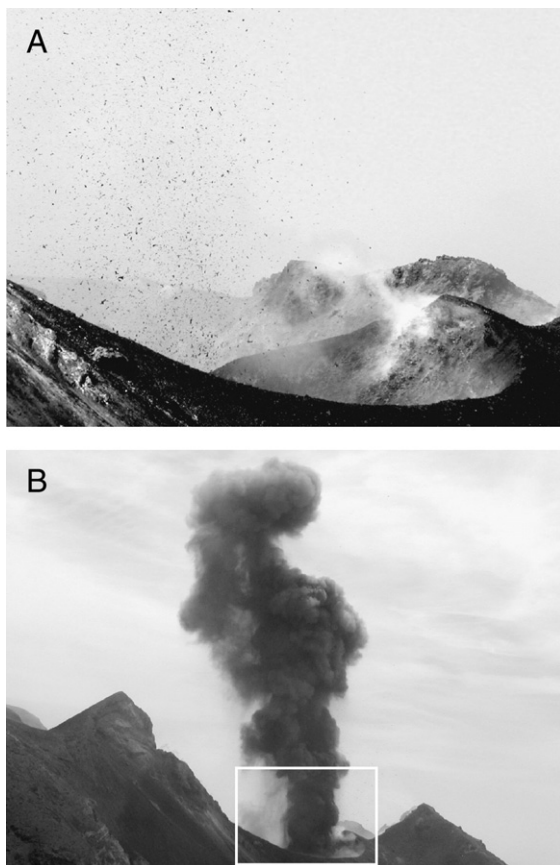


Fig. 2. Type 1 and 2 eruption styles at Stromboli, June 2004. A) Type 1 eruption, which consists of coarse (cm-scale) particles and an ash-free gas plume. The field of view is ~30 high, and is shown by the white box in Fig. 2B. B) Type 2 eruption, which consists of an ash-rich plume. Vertical field of view is ~140 m. The white box corresponds to the field of view in Fig. 2A.

assume that $n_{\text{overall}} \approx n_{\text{plume}}$ in strombolian eruptions because of the potential ballistic abundance and variability in fine ash. The pertinent insights from Rose et al. (1980) are that (1) the plume gas mass fraction is nevertheless sufficiently high to suggest gas decoupling, correctly implying a strombolian eruption mechanism (reinforced by the similarities in scale and intensity) and that (2) the gas mass fraction values in these plumes are much greater than those needed for initial buoyancy.

4. New insights on the gas mass fraction in strombolian eruptions

The range of gas mass fraction values in Blackburn et al. (1976) actually reflect two sets of results (1) those calculated from their estimates of the bulk plume density and (2) those calculated using the assumption that the plumes were the density of air ($\sim 1 \text{ kg m}^{-3}$). The gas mass fraction values for the first set of results ranged from 0.18 to 0.38 for bulk plume densities of 0.51–0.96 kg m^{-3} , while those for the second set ranged from 0.11 to 0.14. The first set of results is problematic because the bulk plume density was calculated using the overall time–height curve over 50–150 m without considering air entrainment over that span. Thus the estimated bulk density is some composite of initial plume density and air density, averaged over an arbitrary height. Their end-member scenario of the bulk density being equal to that of air is predicated on the assumption that the plumes were probably less dense than air; they base this on the observation that convective rise followed the gas-thrust phase. This logic is flawed, however, as even plinian plumes (whose bulk density in the gas-thrust region can be greater than air) convect following the gas thrust phase due to air entrainment. Although their measured density values — for plumes which had substantial air mixed in — were lower than that of air, this does not necessarily imply that the initial density was lower than that of air, due to the non-linear relation between air entrainment and bulk density (Fig. 1B). Thus, although Blackburn et al. (1976) present gas mass fractions for Type 2 activity, the assumptions above make them problematic. Therefore, Rose et al. (1980) seem to provide the most reliable examples of gas mass fraction in strombolian ash plumes.

Another approach is presented here to broadly constrain the gas mass fraction for Type 2 plumes in a simple manner. If we imagine two hypothetical strombolian scenarios, one in which a bubble explodes at the top of a magma column and the high velocity gas entrains no fine particles, and another in which the gas

explodes and mobilizes some amount of fine-grained material, then a simple momentum comparison can be used. The initial momentum of the gas (p_1) unencumbered by particles must equal the momentum of the gas-particle mixture (p_2) because the particles have no initial velocity, so $p_1 = p_2$. This is equivalent to $m_1 u_1 = m_2 u_2$, where m_1 and u_1 are the mass and velocity of the gas alone, respectively, and m_2 and u_2 are the mass and velocity of the mixture of gas and particles. This is then equivalent to:

$$\frac{u_2}{u_1} = \frac{m_1}{m_2} \quad (2)$$

Because the gas mass fraction (n_{plume}) for the second scenario is equal to the gas mass (equivalent to m_1) divided by the combined mass of gas and particles (m_2), we have the following intuitive relation:

$$n_{\text{plume}} = \frac{u_2}{u_1} \quad (3)$$

Note that this equation only applies to eruptions where the particles have no initial velocity. The first and second scenarios can be considered equivalent to Type 1 and 2 eruptions, respectively — i.e. ash-free and ash-rich gas plumes, respectively. Previous work at Stromboli suggests that 120 m s^{-1} is a reasonable upper limit to Type 1 gas velocities (Chouet et al., 1974; Ripepe et al., 1993; Vergnolle and Brandies, 1996; Hort and Seyfried, 1998; Hort et al., 2003; Patrick et al., 2007). We can thus assume that the gas explosion, unencumbered by entrained particles, would have an initial velocity no greater than 120 m s^{-1} . In this case we can calculate a minimum gas mass fraction for strombolian plumes ($n_{\text{plume-min}}$) by comparing observed initial velocities of the ash-rich plumes (u_2) against the highest observed velocity of the ash-free plumes (i.e. 120 m s^{-1} for u_1). This provides a very gross, but nevertheless useful, minimum constraint on the gas mass fraction.

Initial velocities for eight ash plumes at Stromboli were measured by Blackburn et al. (1976) as 28–65 m s^{-1} , and Patrick et al. (2007) measured ash plume velocities at the crater rim for 87 Type 2 ash plumes at Stromboli in 2004 to be between 3 and 58 m s^{-1} . Because the magma interface was some unseen distance beneath the crater rim in the Patrick et al. study, those values represent minimum values for the initial plume velocity. Taken together, these suggest values for $n_{\text{plume-min}}$ between 0.03 and 0.54; with 29% exceeding the highest critical value (0.26) for buoyancy. Unfortunately, in some of the above studies of Type 1 velocities it is unclear how close to the vent the velocity measurements were taken, and thus they could be

somewhat higher. But even given initial gas velocities up to 200 m s^{-1} (likely unrealistically high), at least four $n_{\text{plume_min}}$ values would remain greater than the highest critical value. These values, along with the Rose et al. (1980) results, indicate that strombolian ash plumes can exhibit gas mass fractions far exceeding the critical value (0.14–0.26; Fig. 1A) needed for initial buoyancy. In these cases, the plumes exit the vent with a density less than that of air, and in such instances are thus impervious to column collapse and pyroclastic flow generation. Indeed, of the 150 ash plumes imaged with a FLIR video camera in 2004 at Stromboli (Patrick et al., 2007), none collapsed in whole or in part.

5. Prospects for studying ambiguous eruption styles

Considering the relation of gas mass fraction and bulk density (Fig. 1) together with detailed measurements of plume velocity may help unravel ambiguities surrounding conduit processes and eruption styles at poorly understood volcanoes. For instance, at Santiaguito volcano, Guatemala, small- to moderate-scale ash plumes are erupted approximately 1–2 times per hour, reaching heights of up to 1.2 km above the vent (Bluth and Rose, 2004). The eruption mechanism at this dacitic volcano is not nearly as well-understood as it is at Stromboli, though recent direct imaging of the vent has provided insights on eruptive processes (e.g. Bluth and Rose, 2004). The plumes can erupt with very small initial velocities, ranging from 5 to 30 m s^{-1} (Bluth and Rose, 2004; Johnson et al., 2004). Small pyroclastic flows are created but reflect merapi-style collapse of the crumbling summit dome. Initial velocities as low as 5 m s^{-1} — indicating minimal initial excess momentum — in the absence of column collapse strongly suggest initial buoyancy.

Initial buoyancy discounts the possibility of gas originating strictly from coupled magmatic gas rise (Fig. 1A), and can be explained by one of two scenarios. First, the plumes may be gas-enriched through the involvement of external water, consistent with early work which interpreted the morphology of the ash particles as potentially indicating a phreatomagmatic eruptive origin (Rose et al., 1980; Heiken and Wohletz, 1985). Alternatively, if the erupted gas is purely magmatic this points to decoupled gas rise as a means to explain the high gas mass fractions implied by the initial buoyancy ($n_{\text{plume}} > 0.14\text{--}0.26$; Fig. 1A), in line with more recent work which views the gas as mainly magmatic (Bluth and Rose, 2004). This decoupled gas rise would certainly not resemble strombolian slug flow due to the high viscosity of the dacite magma, but may possibly comprise distributed flow along annular fractures. Gonnerman

and Manga (2003) presented a general model for intermittent permeable fracture networks generated by shear-induced fragmentation along the conduit walls, offering a potential mechanism for this gas decoupling. Bluth and Rose (2004) have previously used the Gonnerman and Manga (2003) model to explain eruptive behavior at Santiaguito. The current study, by supporting the possibility of decoupled gas rise in the conduit, lends further credence to this model for Santiaguito.

6. Conclusions

Plinian plumes result from coupled gas rise in the conduit which leads to low erupted gas mass fractions (< 0.05), resulting in initial bulk densities ($> 3.5 \text{ kg m}^{-3}$) much greater than that of air. Plinian plumes, or any plumes resulting from coupled gas rise in the conduit, therefore depend upon air entrainment in the gas-thrust phase to attain buoyancy — plume collapse and pyroclastic flows occur when entrainment is insufficient. The results in this study show that strombolian ash plumes, which result from decoupled gas rise, can have extremely high gas mass fractions (> 0.30). The gas contents can be sufficient for initial buoyancy ($< 1 \text{ kg m}^{-3}$), which precludes column collapse. Strombolian plumes thus challenge the common notion that inertia-driven plumes are necessarily denser than air. Explosions of decoupled gas may also occur in non-strombolian settings, such as the dacitic system at Santiaguito described above, and thus initially buoyant plumes may be prevalent elsewhere. Considering observed plume dynamics and the gas mass fraction together to better understand gas rise regimes and eruption styles can help determine the propensity for eruption column collapse and resulting hazards.

Acknowledgements

The imaging work at Stromboli was performed in collaboration with A. Harris (Univ. Hawaii Manoa), M. Ripepe (Universita di Firenze), D. Rothery (Open University) and S. Calvari (INGV). This paper further benefited from discussions with G. Bluth, W. Rose, L. Wilson and S. Fagents. The author was supported by NSF grants OISE-0530109 and EAR-0207734 during the writing of the manuscript. Review by A. Burgisser is greatly appreciated.

References

- Blackburn, E.A., Wilson, L., Sparks, R.S.J., 1976. Mechanisms and dynamics of strombolian activity. *Journal of the Geological Society of London* 132, 429–440.

- Bluth, G.J.S., Rose, W.I., 2004. Observations of eruptive activity at Santiaguito volcano, Guatemala. *Journal of Volcanology and Geothermal Research* 136, 297–302.
- Booth, B., Walker, G.P.L., 1973. Ash deposits from the new explosion crater, Etna 1971. *Philosophical Transactions of the Royal Society of London* A274, 147–161.
- Chouet, B., Hamisevicz, N., McGetchin, T.R., 1973. Photoballistics of volcanic jet activity at Stromboli, Italy. *Journal of Geophysical Research* 79, 4961–4976.
- Gonnerman, H.M., Manga, M., 2003. Explosive volcanism may not be an inevitable consequence of magma fragmentation. *Nature* 426, 432–435.
- Heiken, G., Wohletz, K., 1985. *Volcanic Ash*. University of California Press, Berkeley.
- Hort, M., Seyfried, R., 1998. Volcanic eruption velocities measured with a micro radar. *Geophysical Research Letters* 25, 113–116.
- Hort, M., Seyfried, R., Voge, M., 2003. Radar Doppler velocimetry of volcanic eruptions: theoretical considerations and quantitative documentation of changes in eruptive behavior at Stromboli volcano, Italy. *Geophysical Journal International* 154, 515–532. doi:10.1046/j.1365-246X.2003.01982.x.
- Johnson, J.B., Harris, A.J.L., Sahetapy-Engel, S.T.M., Wolf, R., Rose, W.I., 2004. Explosion dynamics of pyroclastic eruptions at Santiaguito volcano. *Geophysical Research Letters* 31, L06610. doi:10.1029/2003GL019079.
- Lautze, N., Houghton, B.F., 2005. Physical mingling of magma and complex eruption dynamics in the shallow conduit at Stromboli Volcano, Italy. *Geology* 33, 425–428. doi:10.1130/G21325.1.
- Murata, K.J., Dondoli, C., Saenz, R., 1966. The 1963–65 eruption of Irazú Volcano, Costa Rica (the period of March 1963 to October 1964). *Bulletin Volcanologique* 29, 765–796.
- Patrick, M.R., Harris, A.J.L., Ripepe, M., Dehn, J., Rothery, D., Calvari, S., 2007. Strombolian explosive styles and source conditions: insights from thermal (FLIR) video. *Bulletin of Volcanology* 69, 769–784. doi:10.1007/s00445-006-0107-0.
- Ripepe, M., Rossi, M., Saccorotti, G., 1993. Image processing of explosive activity at Stromboli. *Journal of Volcanology and Geothermal Research* 54, 335–351.
- Ripepe, M., Marchetti, E., Ulivieri, G., Harris, A.J.L., Dehn, J., Burton, M., Caltabiano, T., Salerno, G., 2005. Effusive to explosive transition during the 2003 eruption of Stromboli volcano. *Geology* 33, 341–344. doi:10.1130/G21173.1.
- Rose, W.I., Chuan, R.L., Cadle, R.D., Woods, D.C., 1980. Small particles in volcanic eruption clouds. *American Journal of Science* 280, 671–696.
- Sparks, R.S.J., Wilson, L., 1976. A model for the formation of ignimbrite by gravitational column collapse. *Journal of the Royal Society of London* 132, 441–451.
- Taddeucci, J., Pompilio, M., Scarlato, P., 2004. Conduit processes during the July–August 2001 explosive activity of Mt Etna (Italy): inferences from glass chemistry and crystal size distribution of ash particles. *Journal of Volcanology and Geothermal Research* 137, 33–54. doi:10.1016/j.jvolgeores.2004.05.011.
- Vergnolle, S., Brandies, G., 1996. Strombolian explosions 1. A large bubble breaking at the surface of a lava column as a source of sound. *Journal of Geophysical Research* 101, 20433–20447.
- Wilson, L., Self, S., 1980. Volcanic explosion clouds: density, temperature, and particle content estimates from cloud motion. *Journal of Geophysical Research* 85, 2567–2572.
- Woods, A.W., 1995. The dynamics of explosive volcanic eruptions. *Reviews of Geophysics* 33, 495–530.