

An inclined Vulcanian explosion and associated products



P. D. Cole^{1, 2, 3*}, A. J. Stinton^{2, 3}, H. M. Odbert^{2, 3, 4}, C. Bonadonna⁵ & R. C. Stewart^{2, 3}

¹ School of Geographical Earth and Environmental Sciences, Plymouth University, Drake Circus, Plymouth PL4 8AA, UK

² Montserrat Volcano Observatory, Flemmings, Montserrat

³ Seismic Research Centre, University of the West Indies, St. Augustine, Trinidad and Tobago

⁴ Department of Earth Sciences, University of Bristol, Queens Road, Bristol BS8 1RJ, UK

⁵ Section des Sciences de la Terre et de l'Environnement, Université de Genève, 13, rue des Maraîchers, CH-1205 Genève, Switzerland

*Correspondence: paul.cole@plymouth.ac.uk

Abstract: Vulcanian explosions generate some of the most hazardous types of volcanic phenomena, including pyroclastic density currents. Non-vertical directionality of an explosion promotes asymmetrical distribution of proximal hazards around the volcano. Although critical, such behaviour is relatively uncommon and has been seldom documented. Here we present, for the first time, evidence both from geophysical monitoring and field survey data that records the occurrence of such an event. Thermal imagery captures a Vulcanian explosion at Soufrière Hills Volcano, Montserrat, which occurred during a large partial lava dome collapse in February 2010, and was inclined at about 25° from the vertical in a northerly direction. Pyroclastic products were preferentially distributed to the north and included: an unusual pumice boulder deposit that we propose was formed by a dilute pyroclastic density current; pumice flow deposits; and a proximal lapilli and block fallout lobe. The inclined nature of the explosion is attributed to the asymmetric geometry around the vent. The explosion-derived pyroclastic density currents had notably lower velocities than those associated with lateral blasts, which, we suggest, result from a separate and distinct mechanism. These inclined explosions present an additional mechanism that is able to generate directed pyroclastic density currents, with consequent implications for hazard assessment.

Received 15 August 2014; revised 21 November 2014; accepted 21 November 2014

Vulcanian explosions occur at many volcanoes around the world (Morrissey & Mastin 2000). They are short-lived events, generally lasting only a few minutes, and evidence indicates that most result from the removal of a rigid ‘cap rock’ or plug obstructing the vent. They typically eject material near vertically as a jet or a series of closely spaced jets (Formenti *et al.* 2003). In most Vulcanian explosions a significant portion of the ejected material rises in a plume, typically between 1 and 15 km in height, with material falling out from this (Bonadonna *et al.* 2002). Ballistic ejecta are also a common feature (Pistolesi *et al.* 2011). In many explosions fountain or column collapse generates pyroclastic density currents that are typically radially distributed around the vent (Druitt *et al.* 2002; Calvari *et al.* 2006).

Between 1995 and 2010 more than 100 relatively large Vulcanian explosions have occurred both during and between the five phases of lava extrusion at Soufrière Hills Volcano, Montserrat (e.g. Druitt *et al.* 2002; Cole *et al.* 2014; Wadge *et al.* 2014). The explosions have occurred as isolated events, as part of month-long sequences, or associated with dome collapse events (Edmonds *et al.* 2006; Loughlin *et al.* 2010; Cole *et al.* 2014). Continuous monitoring of the volcano has allowed detailed documentation of these explosions and coupled with study of the products has allowed unprecedented understanding of the detail of these phenomena. On 11 February 2010 a large partial dome collapse event at Soufrière Hills Volcano took place, which marked the end of the fifth phase of lava extrusion. Seismic and infrasound data indicate that a large Vulcanian explosion took place 87 min after the start of the 107 min long dome collapse event (Stinton *et al.* 2014). The dome collapse generated several pyroclastic density current deposits on the northern flanks. A number of different pumiceous products were associated with the Vulcanian explosion. They are discussed in detail here (Fig. 1).

Here we describe the first example of a Vulcanian explosion at Soufrière Hills Volcano where there is evidence, both directly from

the eruption itself and in the form of the resulting deposits, indicating that the explosion was not vertically directed, but had a significant inclined component. We discuss the possible reasons for this inclined explosion, and describe features of other possible examples of Vulcanian explosions here and elsewhere that might also have had significant non-vertical components, and their potential hazard implications. We also discuss how this type of inclined explosion differs from lateral blasts.

Thermal camera imagery

A thermal camera located 5.75 km to the NW of the volcano (‘MVO’ (Montserrat Volcano Observatory) in Fig. 1) recording images at two frames per second documented the 11 February 2010 dome collapse event. The FLIR A20 camera records thermal wavelengths between 7.5 and 13 µm with a resolution of 0.1 °C and has an angular field of view of 34 × 25°, yielding a 352 × 244 pixel image (see also Delle Donne *et al.* 2014). Recorded values correspond to brightness temperature at these frequencies and are not calibrated for atmospheric attenuation to retrieve absolute surface temperature; we thus analyse these data in relative terms.

The thermal imagery clearly records the explosion starting at 17:20:29 UTC (Fig. 2); it is identified as a pulse of much hotter plume accelerating vertically out of the co-pyroclastic density current ash plume occurring at that time. Part of the explosion plume is obscured by the cooler co-pyroclastic density current plume, as illustrated in Figure 2. The first three pulses of the explosion are described here. Isothermal profiles extracted from the thermal video (Fig. 2) showed that the first pulse of the explosion propagated towards the NE (left) at an angle of c. 25° from the vertical in the plane of the thermal image. We tracked the sharp boundary at the top of the explosion plume through time to estimate a vertical plume velocity of up to 36 m s⁻¹ (see also Cole *et al.* 2014,

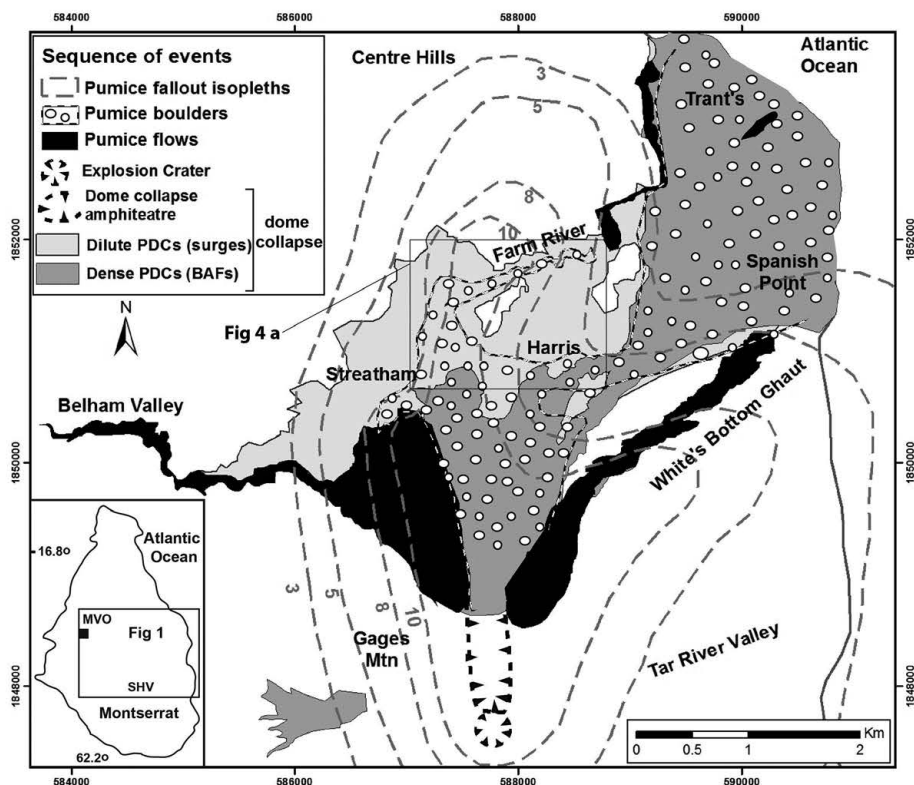


Fig. 1. Map of the northern flank of Soufrière Hills Volcano, Montserrat showing the products of the dome collapse of 11 February 2010 (modified after Stinton *et al.* 2014). Inset shows location of Figure 1 on the island of Montserrat. Grey dashed lines are isopleths (from Cole *et al.* 2014; see that paper for sampling points) of pumice lapilli and block fallout (units in centimetres) formed by the Vulcanian explosion discussed here. BAF, block and ash flow; PDC, pyroclastic density current.

fig. 5.12c). This estimate does not account for the change in the angle of view, which, over the portion of the image under analysis and for a purely vertical plume, would yield velocity estimates about 8% greater. However, given that the imaged plume spreads laterally as it rises, that its inclination in the direction of the camera is not measured, and that the exact source vent location is uncertain (to within hundreds of metres), we estimate a combined velocity error of $\pm 10\%$.

A second, slightly cooler, lower velocity cloud (at +46s) rose subvertically and was followed by a hotter, third pulse (+80s) inclined at an angle similar to the first pulse (Fig. 2).

Deposits

The pyroclastic density currents formed during the dome collapse were predominantly high particle concentration 'block and ash flow' type pyroclastic density currents that remained largely valley-confined and moved to the NE (Fig. 1). However, the largest pyroclastic density currents, which occurred at the climax of the dome collapse (82 min), involved extensive low particle concentration pyroclastic density currents (pyroclastic surges) that swept across a 40° swath of the northern flank, from the NNW (Streatham) to the NNE (Harris). These pyroclastic density currents continued north into the next drainage (Farm River valley) and then moved eastwards and northeastwards towards Trant's (Fig. 1). The deposits of these low-density dome collapse pyroclastic density currents are mainly fine grained, ash rich, and between 10 and 50 cm thick. They were composed of dense or poorly vesicular dome rock and pumice was rare to absent (Stinton *et al.* 2014). The Vulcanian explosion at the end of the dome collapse generated pumice deposits of various forms: as deposits of pumice flows; as lapilli fallout; and also as a distinct deposit of scattered pumice boulders, which show evidence for having been formed by a type of pyroclastic density current. The sequence is capped by up to 10 cm of ash fallout derived from ash plumes associated with the pyroclastic density currents and Vulcanian explosion, within which coarse angular lapilli and block fallout occurs.

Below we describe the details of these pumiceous deposits, as they contain strong evidence for the directed nature of these explosions.

Pumice flow deposits

Pumice flow deposits with narrow (<20 m wide), sinuous lobes hundreds of metres long and typically <1 m thick were formed only in three major drainages on the northern flanks of the volcano: up to 5 km to the NW (Belham Valley), 4 km to the NE (White's Bottom Ghaut), and 7 km to the NNE (Trant's). The pumice flow deposits in White's Bottom Ghaut contained mainly low-density pumice clasts with a relatively narrow range of densities from 300 to 1200 kg m^{-3} (Fig. 3). These deposits were identical, in terms of morphology and clast density, to those formed by fountain collapse-derived pyroclastic density currents associated with many Vulcanian explosions at Soufrière Hills Volcano such as those in 1997 and 2008 (Cole *et al.* 2002, 2014). They are interpreted to have been emplaced as high particle concentration pyroclastic density currents derived from collapsing fountains.

Pumice boulder deposit

A notable deposit of pumiceous boulders and cobbles was emplaced on the northern flank of the volcano. The clasts were semi-rounded to rounded, were typically coarser than 10 cm, and had a maximum length of 120 cm. There was no systematic variation in size of the boulders with distance from the volcano (Fig. 4a). The boulders were dispersed, forming a discontinuous deposit, and were typically embedded in, and in many cases protruding from, the uppermost ash-rich dome collapse-derived pyroclastic density current deposits (Fig. 4b). There was no identifiable fine-grained, pumice-rich matrix (<1 cm) associated with the boulders. Densities of the pumice boulders ranged from 600 to 2500 kg m^{-3} with notably higher densities than the pumice flow deposits (Fig. 3).

In proximal areas <3 km from the vent pumice boulders were relatively unconstrained by topography. At distances >3 km the distribution of the pumice boulders was clearly topographically

The pumice boulders have a wide range of densities, markedly higher than those of the pumice flow deposit (Fig. 3). This density range indicates that the pumice boulders are unlikely to be a type of pumice concentration zone formed in, or segregated from, the upper part of a dense pumice flow deposit. Such a deposit would probably be enriched in low-density pumice, unlike the density range displayed by the pumice boulders. Thus the wide range in

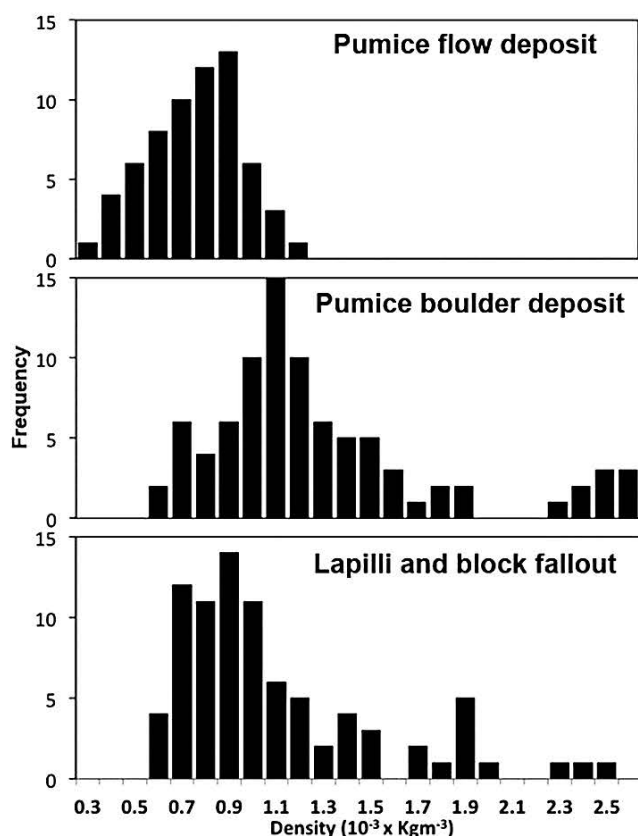


Fig. 3. Histograms showing the frequency v. density of clasts from (top) pumice flow deposits in White's Bottom Ghaut, (centre) pumice boulders 3 km north of volcano, northern part of Farrells plain, and (base) pumice fallout lapilli and blocks from numerous locations. Densities were measured using the Archimedes principle.

clast density implies a direct vent-derived origin rather than formation by segregation from a dense pyroclastic density current.

Lapilli and block fallout

Extensive tephra plumes formed by a combination of the dome collapse pyroclastic density currents and Vulcanian explosion rose to an altitude of 15 km and were affected by a significant fallout decoupling mostly related to both wind shear and the inclination of the convective column. Most of the co-pyroclastic density current and Vulcanian ash reached the umbrella cloud and was dispersed to the SE by the high winds (>5 km) across several islands of the eastern Caribbean (including SE Antigua, Guadeloupe, Dominica and St. Lucia), whereas the Vulcanian lapilli and blocks (up to 15.4 cm across) were deposited to the north and NE (Fig. 1). This is generally consistent with the radiosonde data from Pointe-à-Pitre International Airport, Guadeloupe (80 km to the SE of Montserrat), which show that winds above 5–6 km with velocities between 10 and 35 m s⁻¹ consistently blew to the south and east, and below 5–6 km wind direction was variable with velocities generally <5 m s⁻¹ (Fig. 5).

Lapilli and blocks consist of angular pumice and subordinate dense clasts with densities ranging from 600 to 2500 kg m⁻³, similar to the pumice boulder deposit (Fig. 3). Because of the discontinuous nature of the lapilli and block fallout deposit, an isopach map could not be compiled. However, a clast size isopleth map (three principal axes of the five largest clasts were measured) from more than 100 data points shows that the lapilli and blocks had a marked bilobate distribution, with two coarse lobes: a particularly marked, narrow and coarse-grained one dispersed to the north and a broader, slightly finer-grained lobe to the NE and east (Fig. 1; see

also fig. 5.14 of Cole *et al.* 2014). We consider that the coarse fallout lobe to the north cannot be explained solely by the wind data (Fig. 5).

Owing to their large sizes, sedimentation of lapilli and blocks between 2 and 15 cm is most likely to have occurred from the plume margins and jet. In fact, lapilli and blocks mostly were deposited within the first 5 km from the vent, which roughly corresponds to the position of the plume corner (i.e. 3–4 km from the vent as derived from the equation of Bonadonna & Phillips (2003) for a 15 km high plume). This is confirmed by the comparison between plume ascent velocity and clast terminal velocity, which shows how clasts between 3 and 15 cm sedimented from below 11 km; that is, before reaching the umbrella cloud (Fig. 6). Plume ascent velocities were derived from the numerical solutions to the non-dimensional equations for steady plumes in a stably stratified environment presented by Morton *et al.* (1956) for a 15 km high plume, whereas clast terminal velocities were derived for the turbulent regime assuming spherical shape and a density of 1000 kg m⁻³ (e.g. Bonadonna & Phillips 2003). Our results are also supported by the observations of Bursik *et al.* (1992) and Volentik *et al.* (2010) that showed how only particles <2 cm reached the umbrella cloud for 20–30 km high plumes, which are characterized by even higher velocities than the plume associated with this Vulcanian explosion. Finally, the directionality of the deposition of lapilli and blocks towards the north and NE instead of a symmetrical distribution around the volcano is mostly due to the inclination of the convective column and jet.

Discussion

This is the first example where observational data from an explosion together with detailed studies of the resulting products record evidence of an inclined Vulcanian explosion.

A crater, c. 250 m in diameter and up to 125 m deep, was formed in the summit of the lava dome by the Vulcanian explosion at the end of the partial dome collapse event (Fig. 4e). A notable feature of this explosion crater is its asymmetry; the northern rim is about 90 m lower than the remainder of the crater. The low rim coincides with the headwall of the erosional amphitheatre left from the dome collapse. We propose that the asymmetry formed as a result of excavation of the dome collapse amphitheatre in the northern flank of the lava dome. As a consequence, when the Vulcanian explosion occurred the northern crater rim would have been relatively thin, weak and unsupported, and thus failed preferentially as the explosion initiated.

During the initial moments of the explosion (perhaps contemporaneous with failure of the northern wall of the crater) inclined jets a few hundred metres high were launched onto the northern flanks, forming pumice boulder deposits, which occur in proximal locations on the northern flank up to around 4 km. More distal pumice flow deposits occurred from the Farm River valley NE towards Trant's, to the NW in the Belham valley and to the NE in White's Bottom Ghaut. Therefore we propose that the pumice flow deposits and the pumice boulders were likely to have formed contemporaneously by collapse of the directed fountain onto the northern flank of the volcano as a result of the inclined explosion. By contrast, almost all other Vulcanian explosions at Soufrière Hills Volcano associated with fountain collapse have generated radially distributed pyroclastic density currents (e.g. Druitt *et al.* 2002; Cole *et al.* 2014). The pumice boulders were deposited from a low particle concentration pyroclastic density current that deposited out to 4 km whereas the pumice flow deposits that extend between 4 and 7 km represent high-concentration pyroclastic density currents that formed as the low particle concentration, boulder-rich flow deflated while moving down the Farm River valley.

As the Vulcanian explosion took place, large dome collapse pyroclastic density currents were still moving on the northern

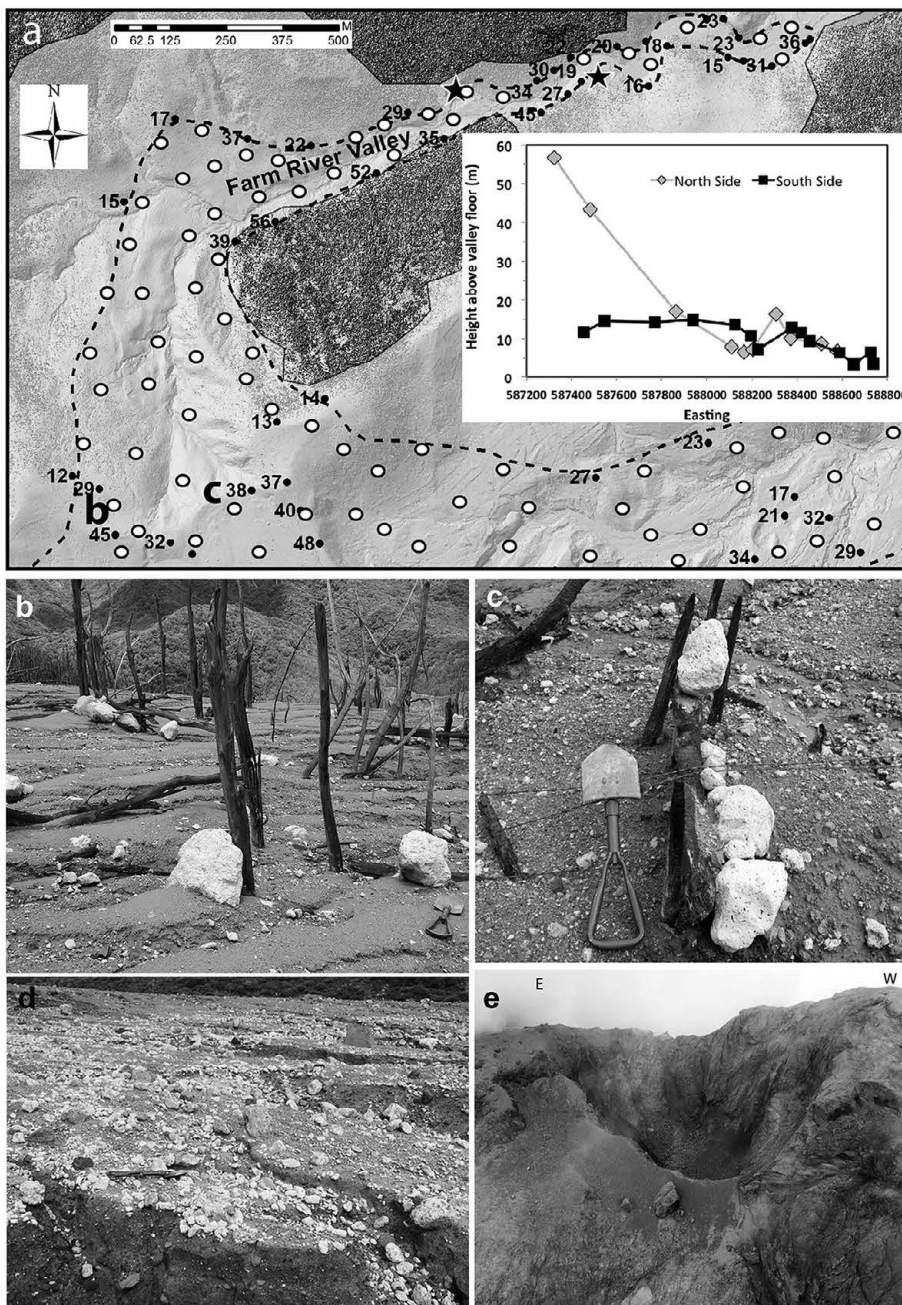


Fig. 4. (a) Map of pumice boulder deposit and mean boulder sizes (average of three principal axes of five largest clasts, values in centimetres) in and around the Farm River valley, between 2.5 and 4 km north of the vent. Inset shows heights (in metres) of upper limit of pumice boulders on the north and south side of the Farm River valley. Filled stars are locations where pumice boulders were found lodged in trees > 2 m above the ground. (b) Pumice boulders at 'b' in (a), resting against charred and abraded trees (3 km north of vent). (c) Detail of rounded pumice boulders wedged between charred tree stumps. Finer angular pumice lapilli fallout in both (b) and (c) should be noted. (d) Pumice boulders on the upper surface of block and ash flow type pyroclastic density current deposits 6 km NE of the volcano. Spade is 55 cm long. (e) The asymmetric crater in the summit of the lava dome formed by the explosion at the end of the dome collapse on 11 February 2010, viewed from the north. The crater is approximately 250 m in diameter.

flank, as indicated by continued elevated seismicity after the explosion. We therefore suggest that the pumice boulders at distances > 4 km from the vent may have been buoyed and transported (piggy-backed) on the upper surface of the pre-explosion block and ash flow-type pyroclastic density currents that were formed by dome collapse.

Deposits from andesitic volcanoes that produce abundant block and ash flows, such as other Lesser Antillean volcanoes, sometimes contain lenses and layers of more pumiceous material (Roobol *et al.* 1987; Smith & Roobol 1990). We proffer that such deposit types may be related to inclined explosions similar to those described here rather than being formed by segregation within a dense pyroclastic density current.

Other inclined explosions at Soufrière Hills Volcano

At least two other Vulcanian explosions at Soufrière Hills Volcano show evidence for having had a significant inclined component. First, the Vulcanian explosion that occurred on 17 September 1996

generated a plume 11 km high and a ballistic field and coarse lobe of lapilli fallout both of which are dispersed to the NE (see fig. 2a of Robertson *et al.* 1998). That explosion occurred a few hours after a significant dome collapse that had excavated a 200 m deep, asymmetric scar in the lava dome that was open to the NE. Regional winds (Guadeloupe airport radiosonde) at the time of this explosion were from the NE below 6 km altitude, and from the north and NW between 6 and 12 km altitude. Thus this NE distribution of coarse lapilli cannot be explained by regional winds; we suggest that it was the result of an inclined explosion from the asymmetric vent area that formed as a result of the dome collapse, in a similar manner to the 11 February 2010 explosion. Again, the lapilli would have fallen out before reaching the umbrella cloud.

Second, on 5 December 2008 a small to moderate-sized Vulcanian explosion at Soufrière Hills Volcano formed a rapidly ascending plume that was inclined to the west (Fig. 7). Furthermore, ballistic fragments were ejected only towards the west to a distance of 2 km ('B' in Fig. 7). The vent was located on the steep western side of the lava dome ('X' in Fig. 7) and we propose that this

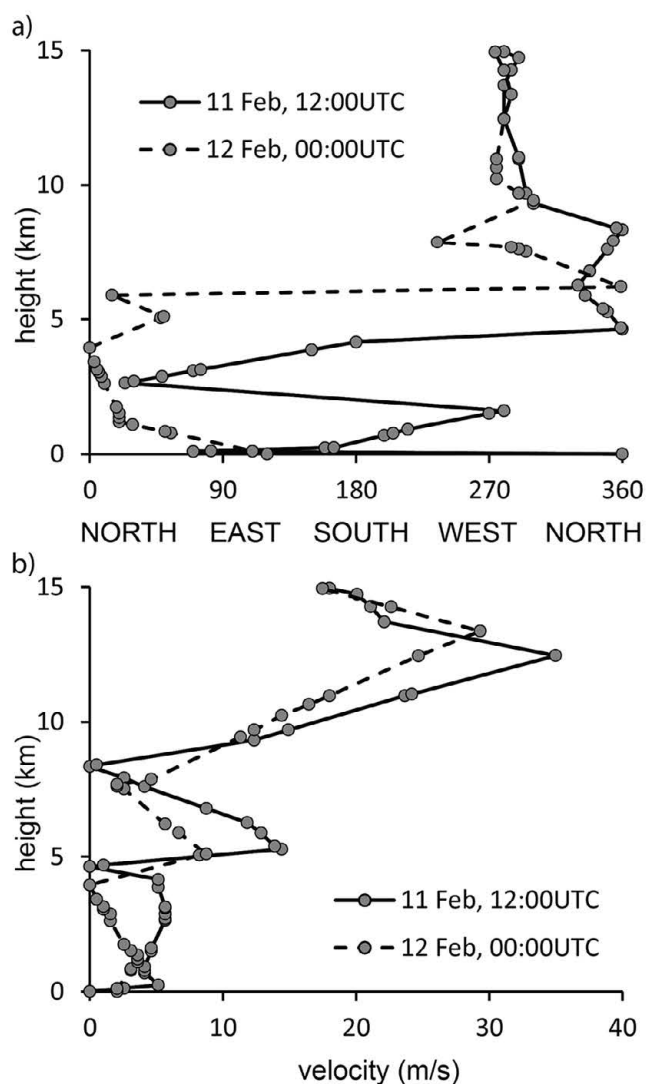


Fig. 5. Wind data from atmospheric air soundings at station TFFR (78897) at Le Raizet, Pointe-à-Pitre, Guadeloupe (80 SE of Montserrat) 12:00 UTC (continuous line) on 11 February 2010 and 00:00 UTC on 12 February 2010. The Vulcanian explosion occurred at 17:20 UTC on 11 February approximately midway between the two sounding times. (a) Wind provenance; (b) wind velocity. Data were obtained from the University of Wyoming (<http://weather.uwyo.edu/upperair/sounding.html>).

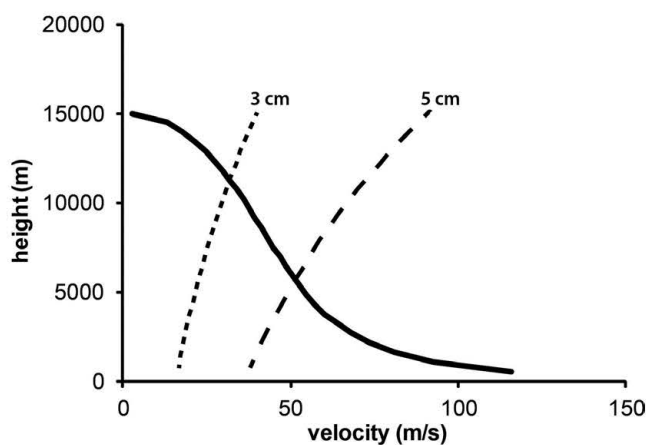


Fig. 6. Comparison between plume ascent velocity (solid line; for a Vulcanian explosion with a plume height of 15 km) and terminal velocity of pumice fragments 15 and 3 cm in diameter (dashed lines) with a mean density of 1000 kg m^{-3} . The intersection between two curves represents the fragment falling height.



Fig. 7. Small inclined explosion at Soufrière Hills Volcano on 5 December 2008 at c. 19:08:30 UTC, 30 s after the onset. Viewed from MVO 5.75 km to the NW of the vent. Ballistic ejecta are visible, causing small plumes of ash where they are striking the ground up to 2 km away on the western flank 'B'. Approximate vent location is marked with an 'X'.

resulted in an asymmetric vent geometry that caused the explosion to be inclined towards the west.

It is worth noting that pyroclastic density currents were not generated in either of these examples of explosive events. We thus infer that the volume of material was not critical in determining whether the explosion was inclined.

Similar events at other volcanoes

To our knowledge, similar inclined explosions generating directed pyroclastic density currents have been described from two other volcanoes. First, photographs of explosive activity in 1984 at Mt. Mayon, Philippines recorded a possible inclined jet forming pyroclastic density currents (Lagmay *et al.* 1999). Modelling by Lagmay *et al.* (1999) showed how an asymmetric crater could direct jets in an inclined manner during explosive activity, forming directional pyroclastic density currents. We consider that similar crater morphology at Soufrière Hills Volcano significantly controlled the inclination of the Vulcanian explosion described here.

Second, explosive activity at Chaiten, Chile in May 2008 generated pumice-rich pyroclastic density currents on the north flank of the volcano. Major *et al.* (2013) interpreted these pyroclastic density currents to have been generated by 'directionally focused' explosions, and evidence indicated that they were dilute, with low dynamic pressures (2–4 kPa) and velocities of the order of $30\text{--}40 \text{ ms}^{-1}$, similar to the velocities estimated for the pyroclastic density currents that emplaced the pumice boulders at Soufrière Hills Volcano.

We consider that inclined explosions are physically distinct from lateral blasts such as those that occurred at Bezymianny in 1956 (Belousov *et al.* 2007), Mount St. Helens in 1980 (Moore & Sisson 1981), and indeed Soufrière Hills Volcano in 1997 (Ritchie *et al.* 2002; Sparks *et al.* 2002). Such lateral blasts are generally associated with large-scale catastrophic failure of part of the edifice of the volcano, which instantaneously unroofs pressurized magma and generates an immediate laterally directed explosion and high-velocity pyroclastic density currents (typically in excess of 100 ms^{-1}).

The inclined explosions described here are not directly associated with rapid failure of the pre-existing edifice in the same way. In the case of Soufrière Hills Volcano, at least, they have been associated with a dome collapse occurring over a period of hours, and the consequent modification to near-vent topography. The

dome collapse, and removal of overburden, was adequate to allow decompression of gas-rich magma within the conduit and the ensuing explosion was then directed away from the vertical owing to the location or configuration of the vent on the edifice. Depending on the volume of material ejected, explosion-derived pyroclastic density currents may or may not be formed, with lateral momentum introduced by the non-vertical component of explosive thrust.

Conclusion

We have demonstrated evidence that Vulcanian explosions can have a notable non-vertical component that results in directed products. Thermal camera imagery, together with three types of pumiceous deposits (proximal lapilli and block fallout, dense pumice flow deposits and a pumice boulder deposit on the northern flanks), records an unusual example of a Vulcanian explosion at Soufrière Hills Volcano that had a marked inclined component to the north.

The inclined explosions generated fountains that collapsed to the north, forming pyroclastic density currents that produced two types of pyroclastic density current deposit. An unusual pumice boulder deposit was formed from the dilute part of the pyroclastic density currents, whereas dense pumice flow type deposits occurred in valleys up to 7 km from the vent. The contemporaneity with dome collapse pyroclastic density currents resulted in some of the pumice boulders being locally transported on the upper surface of still-moving block and ash flow pyroclastic density currents.

Two other examples of Vulcanian explosions at Soufrière Hills Volcano that had inclined components are described; both involved asymmetric vent geometries, although neither generated pyroclastic density currents, with only directed ballistics and dispersed fallout occurring. These other examples indicate that the formation of inclined explosions may not be very unusual and therefore the directed nature of the products, particularly pyroclastic density currents, is an important hazard consideration that may have been overlooked during hazard assessments at other volcanoes.

Acknowledgements and Funding

S. Calvari, S. Watt and an anonymous reviewer improved the paper considerably. Discussions with J. Phillips helped develop the ideas. M. Cassidy is thanked for comments on an earlier version of the manuscript. This work was partly funded by NERC/ESRC project 'Strengthening Resilience in Volcanic Areas' (STREVA).

Scientific editing by Sebastian Watt

References

- Belousov, A., Voight, B. & Belousov, M. 2007. Directed blasts and blast-generated pyroclastic density currents: A comparison of the Bezymianny 1956, Mount St. Helens 1980, and Soufrière Hills, Montserrat 1997 eruptions and deposits. *Bulletin of Volcanology*, **69**, 701–740.
- Bonadonna, C. & Phillips, J.C. 2003. Sedimentation from strong volcanic plumes. *Journal of Geophysical Research*, **108**, 2340, <http://dx.doi.org/10.1029/2002JB002034>.
- Bonadonna, C., Mayberry, G.C., *et al.* 2002. Tephra fallout in the eruption of Soufrière Hills Volcano, Montserrat. In: Druitt, T.H. & Kokelaar, B.P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, **21**, 483–516.
- Bursik, M.I., Sparks, R.S.J., Gilbert, J.S. & Carey, S.N. 1992. Sedimentation of tephra by volcanic plumes: I. Theory and its comparison with a study of the Fogo Aplinian deposit, São Miguel (Azores). *Bulletin of Volcanology*, **54**, 329–344.
- Calvari, S., Spampinato, L. & Lodato, L. 2006. The 5 April 2003 vulcanian paroxysmal explosion at Stromboli Volcano (Italy) from field observations and thermal data. *Journal of Volcanology and Geothermal Research*, **149**, 160–175, <http://dx.doi.org/10.1016/j.jvolgeores.2005.06.006>.
- Chow, V.T. 1959. *Open-Channel Hydraulics*. McGraw-Hill, New York.
- Cole, P.D., Calder, E.S., *et al.* 2002. Deposits from dome-collapse and fountain-collapse pyroclastic flows at Soufrière Hills Volcano, Montserrat. In: Druitt, T.H. & Kokelaar, B.P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat From 1995 to 1999*. Geological Society, London, Memoirs, **21**, 231–262.
- Cole, P.D., Smith, P.J., Stinton, A.J., Odbert, H.M., Bernstein, M.L., Komorowski, J.C. & Stewart, R. 2014. Vulcanian explosions at Soufrière Hills Volcano, Montserrat between 2008 and 2010. In: Wadge, G., Robertson, R.E.A. & Voight, B. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat From 2000 to 2010*. Geological Society, London, Memoirs, **39**, 93–111.
- Delle Donne, D., Ripepe, M., De Angelis, S., Cole, P.D., Lacanna, G., Poggi, P. & Stewart, R. 2014. Thermal, acoustic and seismic signals from pyroclastic density currents and Vulcanian explosions at Soufrière Hills Volcano, Montserrat. In: Wadge, G., Robertson, R.E.A. & Voight, B. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat From 2000 to 2010*. Geological Society, London, Memoirs, **39**, 169–178, <http://dx.doi.org/10.1144/M39.9>.
- Druitt, T.H., Young, S.R., *et al.* 2002. Episodes of cyclic Vulcanian explosive activity with fountain collapse at Soufrière Hills Volcano, Montserrat. In: Druitt, T.H. & Kokelaar, B.P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat From 1995 to 1999*. Geological Society, London, Memoirs, **21**, 281–306.
- Edmonds, M., Herd, R.A. & Strutt, M.H. 2006. Tephra deposits associated with a large lava dome collapse, Soufrière Hills Volcano, Montserrat, 12–15 July 2003. *Journal of Volcanology and Geothermal Research*, **153**, 313–330.
- Formenti, Y., Druitt, T.H. & Kelfoun, K. 2003. Characterisation of the 1997 Vulcanian explosions of Soufrière Hills Volcano, Montserrat, by video analysis. *Bulletin of Volcanology*, **65**, 587–605, <http://dx.doi.org/10.1007/s00445-003-0288-8>.
- Lagmay, M.A., Pyle, D., Dade, B. & Oppenheimer, C. 1999. Control of crater morphology on flow path of Soufrière type pyroclastic flows. *Journal of Geophysical Research*, **104**, 7169–7181.
- Loughlin, S.C., Luckett, R., *et al.* 2010. An overview of lava dome evolution, dome collapse and cyclicity at Soufrière Hills Volcano, Montserrat, 2005–2007. *Geophysical Research Letters*, **37**, L00E16, <http://dx.doi.org/10.1029/2010GL042547>.
- Major, J.J., Person, T.C., Hoblitt, R.P. & Moreno, H. 2013. Pyroclastic density currents associated with the 2008–2009 eruption of Chaiten Volcano (Chile): Forest disturbances, deposits and dynamics. *Andean Geology*, **40**, 324–358.
- Moore, J.G. & Sisson, T.W. 1981. Deposits and effects of the May 18 pyroclastic surge. In: Lipman, P.W. & Mullineaux, D.R. (eds) *The 1980 Eruptions of Mt St. Helens, Washington*. US Geological Survey, Professional Papers, **1250**, 401–420.
- Morrissey, M.M. & Mastin, L.G. 2000. Vulcanian eruptions. In: Sigurdsson, H. (ed.) *Encyclopedia of Volcanoes*. Academic Press, San Diego, CA, 463–476.
- Morton, B., Taylor, G. & Turner, J.S. 1956. Turbulent gravitational convection from maintained and instantaneous source. *Proceedings of the Royal Society of London*, **234**, 1–23.
- Pistolesi, M., Delle Donne, D., Pioli, L., Rosi, M. & Ripepe, M. 2011. The 15 March 2007 explosive crisis at Stromboli Volcano, Italy: Assessing physical parameters through a multidisciplinary approach. *Journal of Geophysical Research*, **116**, B12206, <http://dx.doi.org/10.1029/2011JB008527>.
- Ritchie, L.J., Cole, P.D. & Sparks, R.S.J. 2002. Sedimentology of deposits from the pyroclastic density current of 26 December 1997 at Soufrière Hills Volcano, Montserrat. In: Druitt, T.H. & Kokelaar, B.P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat From 1995 to 1999*. Geological Society, London, Memoirs, **21**, 435–456.
- Robertson, R., Cole, P.D., *et al.* 1998. The explosive eruption of Soufrière Hills Volcano, Montserrat, West Indies, 17 September 1996. *Geophysical Research Letters*, **25**, 3429–3432, <http://dx.doi.org/10.1029/98GL01442>.
- Roobol, M.J., Smith, A.L. & Wright, J.V. 1987. Lithic breccias in pyroclastic flow deposits on St Kitts, West Indies. *Bulletin of Volcanology*, **49**, 694–707.
- Smith, A.L. & Roobol, M.J. 1990. *Mt. Pelée, Martinique: A Study of an Active Island-arc Volcano*. Geological Society of America, Memoirs, **175**.
- Sparks, R.S.J., Barclay, J., *et al.* 2002. Generation of a debris avalanche and violent pyroclastic density current on 26 December (Boxing Day) 1997 at Soufrière Hills Volcano, Montserrat. In: Druitt, T.H. & Kokelaar, B.P. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat, from 1995 to 1999*. Geological Society, London, Memoirs, **21**, 409–434, <http://dx.doi.org/10.1144/GSL.MEM.2002.021.01.18>.
- Stinton, A.J., Cole, P.D., Stewart, R.C., Odbert, H.M. & Smith, P. 2014. The 11 February 2010 partial dome collapse at Soufrière Hills Volcano, Montserrat. In: Wadge, G., Robertson, R.E.A. & Voight, B. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat From 2000 to 2010*. Geological Society, London, Memoirs, **39**, 133–152, <http://dx.doi.org/10.1144/M39.7>.
- Volentik, A.C.M., Bonadonna, C., Connor, C.B., Connor, L.J. & Rosi, M. 2010. Modeling tephra dispersal in absence of wind: Insights from the climactic phase of the 2450 BP Plinian eruption of Pululagua volcano (Ecuador). *Journal of Volcanology and Geothermal Research*, **193**, 117–136, <http://dx.doi.org/10.1016/j.jvolgeores.2010.03.011>.
- Wadge, G., Voight, B., Sparks, R.S.J., Cole, P.D., Loughlin, S.C. & Robertson, R.E.A. 2014. An overview of eruption of Soufrière Hills Volcano, Montserrat from 2000 to 2010. In: Wadge, G., Robertson, R.E.A. & Voight, B. (eds) *The Eruption of Soufrière Hills Volcano, Montserrat From 2000 to 2010*. Geological Society, London, Memoirs, **39**, 1–39, <http://dx.doi.org/10.1144/M39.1>.