An inclined Vulcanian explosion and associated products

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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 pumiceous 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 (Morrisey & 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 × 24°, 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. 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 ±10%.

A second, slightly cooler, lower velocity cloud (at +46 s) rose subvertically and was followed by a hotter, third pulse (+80 s) 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 Ghaunt), and 7 km to the NNE (Trant’s). The pumice flow deposits in White’s Bottom Ghaunt 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 upper-most 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
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controlled and occurred to the north within the Farm River valley and to the NE on the pyroclastic density current fan between Spanish Point and Trant’s (Figs 1 and 4a).

Between 2.5 and 4 km north of the vent numerous pumice boulders occurred resting against upright charred trees, or were wedged between the remains of trees, such as stumps and branches (Fig. 4a and b). Close inspection of the boulders revealed that they were almost always intact and were not fractured or fragmented. Several buildings 3 km to the NNW of the vent had accumulations of pumice cobbles against volcano-facing sides and 2 m inside rooms with intact roofs. The point of entry of these pumice clasts can only have been laterally through window and door openings.

In the Farm River valley, the distribution of the pumice boulders was strongly controlled by topography (Fig. 4a). The upper limit of pumice boulders above the valley floor decreased from 50 to 14 to 5 m from west to east (more proximal to distal) along a 2 km stretch of the Farm River. At bends and constrictions in the valley the upper limit of pumice boulders increased locally (Fig. 4a, inset). Pumice boulders up to 30 cm across were stranded in trees >2 m high up to 14 m above the valley floor (stars in Fig. 4a). Diffusely dispersed pumice boulders also occurred on the upper surface of the more distal block and ash flow deposits to the NE of the volcano (in the region of Trant’s, Farm and Spanish Point). As with the more proximal pumice boulders these clasts were semi-rounded to rounded and were not fractured (Fig. 4b and c).

In proximal areas (<4 km from the vent) features such as the large block size, diffuse and scattered distribution, and absence of an identifiable fine-grained ash matrix indicate that these pumice boulders are similar to ballistic ejecta. However, the rounded nature of the boulders, absence of impact craters, and the existence of intact, unbroken clasts rule out a ballistic emplacement. These features, together with boulders occurring inside houses and banked against volcano-facing sides of buildings, all strongly suggest that the clasts were transported laterally by a pyroclastic density current. Channelling by the strong topography of the Farm River valley is also clear evidence for deposition from a density current.

The run-up heights (h) of the pyroclastic density current using the maximum height of pumice boulders on the northern side of the Farm River valley (50 m) can be used to estimate the velocity (v) of the pyroclastic density current using the equation \( v^2 = 2gh \) (Chow 1959), and yield a velocity of 31 m s\(^{-1}\). Boulders (up to 30 cm in diameter) stranded up to 15 m above the Farm River valley floor (and lodged within trees) indicate that the parent pyroclastic density current was inflated, with a low particle concentration. Furthermore, the decreasing height of the stranded pumice boulders above the valley base from west to east in the Farm River valley (Fig. 4, inset) suggests that expansion of the pyroclastic density current diminished as it moved down the valley.

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. 2.** Profiles from thermal video showing the plume outline during the initial three pulses of the Vulcanian explosion that started at 17:20:29 UTC. The uppermost outline of the plume was traced at 2 s intervals from frames of thermal video, as illustrated in the lower three panels. The outline of volcano topography is shown for reference and the approximate explosion source location is marked with an ‘X’. A region of each image frame where the explosion plume was obscured by cooler, dome collapse-related pyroclastic density current ash cloud is indicated. The left-hand panels show the first pulse; bold lines contour the plume outline developing at successive 2 s intervals. Dashed lines show the directions of highest jet velocity. In the middle and right-hand panels, the equivalent contours are shown for the second and third pulses. The time span, in seconds from the explosion onset, is shown for each set of contours.
a broader, slightly finer-grained lobe to the NE and east (Fig. 1; see marked, narrow and coarse-grained one dispersed to the north and marked bilobate distribution, with two coarse lobes: a particularly more than 100 data points shows that the lapilli and blocks had a (three principal axes of the five largest clasts were measured) from lar to the pumice boulder deposit (Fig. 3). Because of the discon- erally <5 m s\(^{-1}\) (Fig. 5).

and below 5–6 km wind direction was variable with velocities gen-

Densities were measured using the Archimedes principle.

boulders 3 km north of volcano, northern part of Farrells plain, and (top) pumice flow deposits in White's Bottom Ghaut, (centre) pumice

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.

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 have 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\(^{-3}\), simi-
lar to the pumice boulder deposit (Fig. 3). Because of the discon-
tinuous 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 cor-

Discussion

This is the first example where observational data from an explo-

tion 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 unsup-

ported, and thus failed preferentially as the explosion initiated.

During the initial moments of the explosion (perhaps contempo-

raneous 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 loca-

tions 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 depos-

its and the pumice boulders were likely to have formed contempo-

raneously by collapse of the directed fountain onto the northern flank of the volcano as a result of the inclined explosion. By con-

trast, 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,oulder-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
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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
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 30–40 m s\(^{-1}\), 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 m s\(^{-1}\)).

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 fall-out 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. Calvani, 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

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