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Volcanic plume and bomb field masses from thermal infrared camera imagery

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ABSTRACT

Masses erupted during normal explosions at Stromboli volcano (Italy) are notoriously difficult to measure. We present a method that uses thermal infrared video for cooling bomb fields to obtain the total power emitted by all hot particles emitted during an explosion. A given mass of magma (M) will emit a finite amount of thermal power, defined by $M\,c_p(T_e-T_0)$, c_p and T_e being magma specific heat capacity and temperature, and T_0 being ambient temperature. We use this relation to convert the total power emitted by the bomb field to the mass required to generate that power. To do this we extract power flux curves for the field and integrate this through time to obtain total power (E). This is used to estimate mass (Q) in $Q=E/c_p(T_e-T_0)$. When applied to individual bombs we obtain masses of between 1 and 9 kg per bomb, or a volume of 970 and 6500 cm^3. These volumes equate to spheres with diameters 12 and 27 cm. For the entire bomb field we obtain volumes of 7–28 m^3. We calculate masses for 32 eruptions and obtain typical bomb masses of between 10^3 and 10^4 kg per eruption. In addition, we estimate that between 10^2 and 10^3 kg of gas and ash are emitted as part of a mixed plume of bombs, gas and ash. We identify two types of eruption on the basis of the erupted bomb masses and the ratio of the plume's gas-and-ash component to the bomb component. The first type is bomb-dominated, is characterized by bomb masses of 10^4 kg and has ash–gas/ bomb ratios of $\sim$0.02. The second type is ash-and-gas dominated, is characterized by erupted bomb masses of 10^3 kg and has ash–gas/bomb ratios of around one, and as high as two. There is no correlation between the quantity of bombs and quantity of gas–ash erupted. In addition, while source pressure for each explosion correlates with the quantity of gas and ash erupted, the mass of bombs emitted varies independently of pressure.

1. Introduction

Normal explosive eruptions at Stromboli volcano (Aeolian Islands, Italy) typically involve ejection of a mixed plume of gas, ash and bombs (e.g., Chouet et al., 1974; Ripepe et al., 1993; Patrick et al., 2007). The generally accepted model to explain this activity is the repeated ascent of large gas bubbles, or slugs, that burst at the free surface of the magma column (e.g., Blackburn et al., 1976; Jaupart and Vergniolle, 1988; Parfitt and Wilson, 1995). Bursting generates a cloud of bombs, ash and gas which ascends the empty section of the conduit to be released at the vent as an eruption plume (e.g., Jaupart and Vergniolle, 1989; Ripepe et al., 2001, 2002). The ensuing emission comprises two components: the first comprises bomb sized fragments which follow ballistic trajectories; the second comprises a cloud of finer particles and gas whose ascent shows a gas thrust phase followed by buoyant ascent (Patrick et al., 2007).

The mass and volume of both gas and solid particles ejected during a single explosion, as well as their relative proportions, is a critical yet illusive measurement. It is a crucial parameter to have in hand if we are to fully parameterize and classify a Strombolian explosion (e.g., Walker, 1973; Chouet et al., 1974; Blackburn et al., 1976), as well as to understand and model the explosion mechanism that feeds the eruption (e.g., Parfitt and Wilson, 1995; Vergniolle et al., 1996; Parfitt, 2004). Modeling the ascent and dispersion dynamics of bomb-loaded plumes also requires knowledge of the particle size and number, as well as the mass of both the gaseous and solid components (e.g., Wilson and Self, 1980; Fagents and Wilson, 1993; Capaccioni and Cuccoli, 2005). System mass balance studies aimed at constraining the imbalance between degassed and erupted masses, by definition, also require reliable measurements of both degassed and erupted masses (e.g., Francis et al., 1993; Allard et al., 1994; Harris and Stevenson, 1997a). The problem is, Strombolian eruptions are typically characterized by repeated explosive emissions of unpredictable eruption interval that emit centimeter-to-meter sized particles, which are defined as bombs if they attain a diameter of greater than 6.4 cm (Cas and Wright, 1987). These land in a discontinuous

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Table 1
Published values for mass (in kg) ejected during normal explosions at Stromboli. Summary results from this study combined the data for eruptions from the SW crater (3 eruptions) and the NE1 vent of the NE Crater (16 eruptions) as given in Appendix B.

	Chouet et al. (1974)	Blackburn et al. (1976)	Ripepe et al. (1993)	Patrick (2005)	This study
No.	2	8	10	344	19
Ejected Mass (kg)					
Min.	8	16	210	0	900
Mean	–	1230	6250	500	9600
Max.	100	5990	31,800	6230	34,700

field close to the vent, making approach of the deposit for field measurement and sample return (for mass and volume constraint of the solid component of the emission) a difficult task.

Close approach to the vent, where the bomb field lies, is certainly a dangerous undertaking due to the risk of collector-impact during the next explosion. Vents are also often located within steep-sided pit craters, making them inaccessible. As a result, our understanding of the mass of solid particles ejected during an individual eruption has relied on remote sensing data. These data have typically been provided by ground-based cameras operating at high spatial resolutions and frame rates. Those rare measurements for masses of individual Strombolian explosions that exist have tended to use visible to near infrared camera stills to obtain the mass of all particles during flight (Chouet et al., 1974; Blackburn et al., 1976; Ripepe et al., 1993), with all three of these studies targeting normal explosive emissions at Stromboli. These results are collated in Table 1 and together yield data for 20 eruptions. Later, Patrick (2005) used thermal video to estimate the mass of all particles during flight. The technique of Patrick (2005) used the area of high temperature particles observed in sequential image stills and applied a shape assumption to obtain the volume of the particles. However, the measurement suffered from problems of double counting and thus gave an estimate of the bomb mass from the maximum value obtained from any single still obtained during the video sequence for the entire emission. We here present a new method for estimating bomb field mass which uses thermal infrared image data for the static, cooling bomb field. We present results for a further 32 eruptions, thereby doubling the amount of data available for studying and modeling the dynamics of Strombolian eruptions.

2. Experiment location and set-up

Stromboli is well known for its persistent mildly explosive style of activity that has likely been more or less continuous since between the third and seventh centuries AD (Rosi et al., 2000). Normal activity at Stromboli is characterized by repeated explosive events lasting a few seconds to tens of seconds and involves emission of jets and bursts of gas, ash and incandescent magma fragments to heights of between 100 m and 200 m (Barberi et al., 1993). Eruption frequencies are variable, but have a typical (time-averaged) rate of ~9 events/h (Harris and Ripepe, 2007). Activity has been localized at three main craters at least since 1776 when Stromboli was visited by Hamilton (Washington, 1917). The three craters (SW, Central and NE) are located at an elevation of ~800 m and, together, have a SW–NE dimension of ~250 m. Bomb-sized particles follow ballistic trajectories to land within the crater zone, typically landing no more than 100 m from the vent. The reliability of explosive activity, and the relatively safe viewing from distances as close as 250 m, has made Stromboli a popular target for measurements that seek to parameterize and understand the dynamics of the emissions associated with such explosive activity (e.g., Chouet et al., 1974; Ripepe et al., 1993; Patrick et al., 2007).

We deployed a thermal video camera to measure the temperature of individual bombs within cooling bomb fields between 30 May and 8 June 2008, as well as on 1 June 2010, during a period of typical, normal, explosive activity. The camera used was a FLIR systems S40 which collects 320 × 240 pixel images in the thermal infrared (7.5–13 μm), with each pixel having an instantaneous field of view (IFOV) defined by an angle of 1.3 mrad. We collected imagery via a fire-wire connection to a laptop at frame rates of 7.5 Hz using the camera's mid-range gain setting. This allows measurement of pixel-integrated temperatures in the range 0–500 °C. Upon landing, bomb exteriors had cooled to such an extent that no saturation was experienced using this range, pixel-integrated temperatures for bomb-containing pixels typically being in the range 90–190 °C. Temperatures were corrected for emissivity and atmospheric effects using the camera's on-board (MODTRAN-based) software and inputting measurements of air temperature and humidity, obtained at the measurement site every 15 min. The camera was pointed not at the sky above the vent to capture the plume ascent, but at a zone below the vent in which the bombs fell; thus allowing data for the size, area and cooling properties of the bomb field to be estimated. However, because the plume was not imaged, no information regarding the plume dynamics could be extracted from this imagery.

During June 2008 a vent active within the SW crater was targeted from Pizzo Sopra la Fossa. The vent was visible on the crater floor, meaning that the entire bomb field was imaged as it cooled (Fig. 1a and b). The line-of-sight distance (D_{LOS}) to the vent (as measured with a laser range finder) was 227 m, with the camera being tilted downwards at an angle of 25°. Oblique viewing will induce pixel distortion. Pixel dimension (D_{pixel}) for surface orientated at right-angles to the camera can be estimated from the simple geometric relation $D_{pixel}=2[D_{LOS}\tan(\mathrm{IFOV})]$. However, viewed at a downward pointing angle of θ, the adjusted pixel dimension (D_{adjust}) will be $D_{pixel}/\sin(\theta)$ for a flat surface or $D_{pixel}/\sin(\beta)$ for a vertical surface, β being 90 minus θ. Thus, for our case we have square pixel area of 0.09, 0.49 and 0.11 m^2 for the three cases, respectively. During June 2008 two vents active within the NE crater were targeted (Fig. 1c and d). The crater was shallow and emissions from one of the vents (NE1) were directed towards the camera site so that most, if not all, of the bomb field was imaged as it cooled (Fig. 1d). The line-of-sight distance to the vent was 400 m, with the camera being positioned so that the surface was orientated more or less at right-angles in respect to the image plane, so that the pixel area at the bomb field was 0.27 m^2.

A second camera, permanently located at a site ~500 m NE of the active craters, was used to extract the dynamic properties of the ascending cloud (velocity, volume flux and maximum temperature). This camera was a FLIR A20, which collects 160 × 120 pixel images and is sensitive in the 7.5–13 μm waveband. Images were transmitted to a reception site on the island where they were processed and archived 5 times a second, giving a frame rate of 5 Hz. The A20 camera targeted the plumes as they ascended above the vent, but not the bomb field. Thus the two cameras, permanent and temporary, were used to extract information regarding the ascending plume and its associated bomb field, respectively. All camera specifications, location and line of sight details are given in Appendix A.

3. Method

3.1. Total bomb mass from bomb field power loss

Radiative and convective power flux densities (q_{rad} and q_{conv}, in W m^{-2}) for a hot particle at temperature T can be obtained