



SAPIENZA
UNIVERSITÀ DI ROMA

**FACOLTÀ DI SCIENZE MATEMATICHE FISICHE E NATURALI
DIPARTIMENTO DI SCIENZE DELLA TERRA**

DOTTORATO DI RICERCA XXXI CICLO

**STROMBOLIAN EXPLOSIONS: RELATIONSHIPS
BETWEEN THE CONDUIT SYSTEM AND THE
RESULTING EXPLOSIVE ACTIVITY AT THE VENTS**

Docente guida:

Prof. Danilo Mauro Palladino

Candidato:

Valentino Salvatore

Correlatore:

Dott. Jacopo Taddeucci (INGV)

Anno Accademico 2017–2018



SAPIENZA
UNIVERSITÀ DI ROMA

STROMBOLIAN EXPLOSIONS: RELATIONSHIPS BETWEEN THE CONDUIT SYSTEM AND THE RESULTING EXPLOSIVE ACTIVITY AT THE VENTS

**Facoltà di Scienze Matematiche Fisiche e Naturali
Dipartimento di Scienze della Terra
Dottorato di ricerca XXXI ciclo**

**Valentino Salvatore
Matricola 1253163**

Docente guida
Prof. Danilo Mauro Palladino

Correlatore
Dott. Jacopo Taddeucci (INGV)

A.A. 2017–2018

ABSTRACT

Persistent, open-vent volcanoes frequently host Strombolian explosions. This style of activity is characterized by frequent (intervals of seconds to minutes) and impulsive (seconds-long) releases of pyroclasts and gases, due to the rise and burst of large gas bubbles (i.e., *slugs*) near the surface of the magma column. Over time, such volcanoes can show continuous changes in the evolution and migration of their active vents, from which also a highly variable behavior of the activity can be observed. The sources of such variability need being investigated at variable spatial and temporal scales. On a scale of years/hundred of meters, direct observation of space-time vent migration at multi-vent volcanoes is still limited, and the relationship between this variable activity and the shallow conduit system remains to be understood. On a scale of seconds/meters, many authors are focused on the dynamics of gas release and modes of pyroclasts formation, so far largely neglecting the ascent dynamics of pyroclasts from their release depth, where slugs burst, to their ejection from the vent. The aim of my study is the definition of the relationships between the physical parameters inside the volcanic conduit and their influence on the modes of pyroclast ejection in Strombolian explosions, accounting for the two scales abovementioned. To achieve this aim, I considered two separate yet complementary methodologies.

The first one requires the characterization of Strombolian eruptions in nature investigating temporal changes in vent position at the crater terrace of Stromboli and explosion parameters (jet duration and geometry) using infrared surveillance camera videos collected between 2005 and 2009. Results by this first methodology provide a detailed database of normal Strombolian activity at different time-scales, as well as allowing one to outline a hierarchy of depths at which the shallow conduit system controls the explosive activity within the three main vent areas (i.e., south-west, central, and north-east) at Stromboli. At the shallowest depth, where slugs burst, vent shape and slug size control local explosion parameters, while shallower conduit branching determines the evolution of simultaneous or alternating twin vents. Below the depth of the slug burst, the conduit system feeding each vent area controls which specific vent will host the explosions and also some more general explosion features within a vent area. A link between the central and south-west vent areas is supposed at this depth, as supported by several observations. At the deepest level, the conduit system is common to all vent areas and sets the overall explosion rate of the

volcano, balancing it between the north-east and the joint south-west and central vent areas. This kind of analysis may be performed also in other persistent multi-vent systems worldwide, providing basic inferences on geometry and dynamics of their conduit systems and on the hazard assessment.

The second methodology is addressed on gas-particle jet simulations by means of scaled analogue experiments using a transparent shock-tube. This approach focuses on the effect of the initial source conditions (i.e., gas pressure and volume, sample position, size and amount of particles, vent geometry) both on the acceleration of the particles within the conduit and on the resulting ejection from the vent. Results show that maximum particle velocity has a strong positive correlation with initial energy and a weaker, negative correlation with both sample depth from the vent and particle size. Moreover, the experiments show trends of particle acceleration-deceleration in the shock-tube that variably depend on some initial conditions (i.e., initial energy, sample depth, and particle size) and influence particle maximum velocity recorded at the exit. When compared to processes occurring during low-scale explosive eruptions, these results open the way for potential, new inferences on the processes controlling the dynamics of pyroclasts. The acceleration-deceleration trends inside the conduits impact current models relating pyroclast ejection velocity with their source depth in the volcanic conduit. I show that, for a lower initial energy and a deeper sample, the model assumptions do not hold true anymore. Therefore, a model revision taking into account these trends is necessary before applying it to real eruptions. These results open the way to numerous future scenarios. Further experiments may, for instance, clarify, the effects of particle-gas coupling, analyze the role of other source parameters on pyroclast ejection (e.g., conduit diameter) and study other aspects (e.g., the volcanic plumes using very fine particles, or particle-particle and particle-wall collisions in the conduit).

I vulcani in stato di attività persistente a condotto aperto spesso ospitano un'attività definita stromboliana. Questo stile di attività è caratterizzato da rilasci frequenti (intervalli da secondi a minuti) e impulsivi (della durata di alcuni secondi) di piroclasti e gas, dovuti alla risalita e allo scoppio di grosse bolle di gas (dette *slug*) vicino alla superficie della colonna di magma. Nel tempo, tali vulcani possono mostrare continui cambiamenti nell'evoluzione e nella migrazione delle proprie bocche attive, dalle quali si può osservare anche un comportamento altamente variabile dell'attività. Le origini di tale variabilità devono essere studiate a scale spaziali e temporali variabili. In una scala di anni/centinaia di metri, l'osservazione diretta della migrazione delle bocche nello spazio e nel tempo nei vulcani contraddistinti da più bocche è ancora limitata, e resta da capire la relazione tra questa attività variabile e il sistema di condotti superficiale. Su una scala di secondi/metri, molti autori si sono focalizzati sulla dinamica del rilascio di gas e sulle modalità di formazione dei piroclasti, finora trascurando ampiamente la dinamica di risalita dei piroclasti dalla profondità di rilascio, dove gli *slug* scoppiano, sino alla loro espulsione dalla bocca. Lo scopo del mio studio è la definizione delle relazioni tra i parametri fisici all'interno del condotto vulcanico e la loro influenza sulla modalità di espulsione dei piroclasti nelle eruzioni stromboliane, tenendo conto delle due scale sopramenzionate. Per raggiungere tale scopo ho adottato due metodologie separate ma complementari.

La prima richiede la caratterizzazione delle eruzioni stromboliane in natura, indagando i cambiamenti temporali nella posizione delle bocche sulla terrazza craterica di Stromboli e i parametri di esplosione (durata e geometria del getto) usando i video delle telecamere di sorveglianza a infrarossi raccolti tra il 2005 e il 2009. I risultati di questa prima metodologia forniscono un database dettagliato dell'attività stromboliana normale a diverse scale temporali, oltre a consentire di delineare una gerarchia di profondità a cui il sistema di condotti superficiale controlla l'attività esplosiva entro le tre principali aree (cioè la nord-est, la centrale e la sud-ovest) che raggruppano più bocche vicine a Stromboli. Alla profondità più bassa, dove gli *slug* scoppiano, la forma della bocca e le dimensioni degli *slug* controllano i parametri di esplosione locali, mentre la ramificazione più in superficie dei condotti determina l'evoluzione delle bocche che esplodono simultaneamente o alternativamente. Al di sotto della profondità di scoppio degli *slug*, il sistema di condotti che alimenta ciascuna area

di bocche controlla quale specifica bocca ospiterà le esplosioni e anche alcune caratteristiche generali di esplosione all'interno di queste aree. A questa profondità si suppone ci sia un collegamento tra l'area centrale e quella sudovest, come supportato da diverse osservazioni. Al livello più profondo, il sistema di condotti è comune a tutte le aree e imposta il tasso eruttivo globale del vulcano, bilanciandolo tra l'area nord-est e quella congiunta sud-ovest e centrale. Questo tipo di analisi può essere eseguito anche in altri sistemi persistenti contraddistinti da più bocche in tutto il mondo, fornendo deduzioni di base sulla geometria e la dinamica del loro sistema di condotti e sulla valutazione della pericolosità connessa.

La seconda metodologia è dedicata alle simulazioni di getti gas-particelle per mezzo di esperimenti analogici in scala utilizzando uno *shock-tube* trasparente. Questo approccio è incentrato sull'effetto delle condizioni iniziali (cioè, pressione e volume del gas, posizione del campione, dimensione e quantità di particelle, geometria della bocca) sia sull'accelerazione delle particelle all'interno del condotto che sull'espulsione risultante dalla bocca. I risultati mostrano che la velocità massima delle particelle ha una correlazione positiva con l'energia iniziale e una correlazione negativa sia con la profondità del campione rispetto alla bocca che con la dimensione delle particelle. Inoltre, gli esperimenti mostrano tendenze di accelerazione e decelerazione delle particelle all'interno dello *shock-tube* che dipendono in modo variabile da alcune condizioni iniziali (cioè energia iniziale, profondità del campione e dimensione delle particelle) e influiscono sulla velocità massima delle particelle registrata all'uscita. Rispetto ai processi che si verificano durante le eruzioni esplosive a piccola scala, questi risultati aprono la strada a nuove potenziali deduzioni riguanti i processi che controllano la dinamica dei piroclasti. Le tendenze di accelerazione e decelerazione all'interno dei condotti influenzano i modelli correnti che correlano la velocità di espulsione dei piroclasti con la loro profondità di origine nel condotto vulcanico. Dimostro che le assunzioni del modello non sono più valide nei casi di bassa energia iniziale e un campione più profondo. Pertanto, è necessaria una revisione del modello che tenga conto anche di queste tendenze prima di applicarlo alle eruzioni reali. Questi risultati aprono la strada a numerosi scenari futuri. Ad esempio, ulteriori esperimenti possono chiarire meglio gli effetti dell'accoppiamento gas-particella, analizzare il ruolo di altri parametri sull'espulsione dei piroclasti (ad esempio il diametro del condotto) o studiare altri aspetti (ad esempio, i pennacchi vulcanici utilizzando particelle molto fini, o collisioni particella-particella e particelle-parete nel condotto).

TABLE OF CONTENTS

ABSTRACT	I
RIASSUNTO	III
CHAPTER 1 – INTRODUCTION	1
CHAPTER 2 – PARAMETERIZING MULTI-VENT ACTIVITY AT STROMBOLI VOLCANO (AEOLIAN ISLANDS, ITALY)	6
2.1 INTRODUCTION	7
2.2 GEOLOGICAL SETTING	8
2.3 METHODS	10
2.4 RESULTS	12
<i>2.4.1 EVOLUTION AND MIGRATION OF THE ERUPTIVE VENTS</i>	<i>14</i>
<i>2.4.2 EXPLOSION FREQUENCY</i>	<i>15</i>
<i>2.4.3 EXPLOSION FEATURES</i>	<i>16</i>
2.5 DISCUSSION	22
<i>2.5.1 SINGLE/TWIN VENTS: HOURS-DAYS</i>	<i>23</i>
<i>2.5.2 SINGLE/TWIN VENTS: MONTHS-YEARS</i>	<i>24</i>
<i>2.5.3 VENT AREAS: HOURS-DAYS</i>	<i>25</i>
<i>2.5.4 VENT AREAS: MONTHS-YEARS</i>	<i>26</i>
<i>2.5.5 HYPOTHETICAL SCHEME OF THE SHALLOW CONDUITS</i>	<i>28</i>
2.6 CONCLUSIONS	30
2.7 ACKNOWLEDGEMENTS	31
2.8 FUNDING INFORMATION	31
CHAPTER 3 – CONDUIT PYROCLAST DYNAMICS IN STROMBOLIAN EXPLOSIONS IN LIGHT OF SHOCK-TUBE EXPERIMENTS	32
3.1 INTRODUCTION	33
3.2 METHODS	36
<i>3.2.1 THE EXPERIMENTAL TOOL: THE JET-BURSTER</i>	<i>36</i>
<i>3.2.2 VIDEO ANALYSIS</i>	<i>39</i>
<i>3.2.3 SCALING</i>	<i>40</i>
3.3 RESULTS	43
<i>3.3.1 THE SHOCK-TUBE PROCESSES</i>	<i>43</i>
<i>3.3.2 INFLUENCE ON PARTICLE EJECTION</i>	<i>47</i>
<i>3.3.3 PARTICLE ACCELERATION AND DECELERATION</i>	<i>50</i>
3.4 DISCUSSION	53
<i>3.4.1 GAS-PARTICLE DYNAMICS IN THE CONDUIT</i>	<i>54</i>
<i>3.4.2 INFERENCES ON THE DERIVED DEPTH OF FRAGMENTATION LEVEL</i>	<i>56</i>
3.5 CONCLUSIONS	57
3.6 ACKNOWLEDGEMENTS	59
CHAPTER 4 – CONCLUDING REMARKS	60

APPENDIX A – ENLARGED VERSIONS OF TIME WINDOW PLOTS	64
APPENDIX B – REYNOLDS AND STOKES NUMBERS AT STROMBOLI	70
APPENDIX C – DERIVATION OF MACH NUMBER AND T FOR EQUATION (6)	72
REFERENCES	75
ACKNOWLEDGEMENTS	92

CHAPTER 1 – INTRODUCTION

Worldwide, a number of volcanoes manifests an activity defined persistent, consisting of eruptions that continue for long periods (thousands of years, Rosi et al. 2000, 2013). Frequently, this activity is characterized by *Strombolian explosions*, which is an eruptive style recognized at several other active volcanoes beyond Stromboli (from which this activity takes its name, Mercalli 1907), such as Masaya (Nicaragua; Rymer et al. 1998), Pu'u 'O'o (Hawaii; Marchetti and Harris 2008), Etna (Italy; Cannata et al. 2011), Fuego (Guatemala; Waite et al. 2013), and Yasur (Vanuatu; Gaudin et al. 2014). Typical Strombolian activity is characterized by frequent (intervals of seconds to minutes) and impulsive (second-long) releases of pyroclasts and gases (Chouet et al. 1974; Parfitt and Wilson 1995; Ripepe et al. 1996; Oppenheimer et al. 2006; Gaudin et al. 2014; Taddeucci et al. 2015), due to the rise and burst of large gas bubbles (i.e., *slugs*, Blackburn et al. 1976; Sparks 1978; Jaupart and Vergnolle 1988; Parfitt 2004; Burton et al. 2007; Patrick et al. 2007; James et al. 2009; Chouet et al. 2010; Capponi et al. 2016) on the surface of the magma column. Many studies have constrained the depth where slugs may burst; for instance, at Stromboli this depth is between 0 and 150 m from the vent (e.g., Ripepe et al. 2001, 2002; Gurioli et al. 2013; Gaudin et al. 2014). The normal Strombolian activity is sporadically interrupted by higher intensity *paroxysmal eruptions*, occurring with an interval of about a few years and showing columns almost 10 km high (e.g., Rittmann 1931; Barberi et al. 1993; Bertagnini et al. 1999; Calvari et al. 2005; Bertagnini et al. 2008; Landi et al. 2008; Barberi et al. 2009; Métrich et al. 2010; Gurioli et al. 2013). This unusual activity, classified as *violent Strombolian activity* by Valentine and Gregg (2008), can completely modify the structural layout of the crater terrace.

Mildly explosive, open-vent, volcanoes with persistent activity are subject to continuous modifications within their crater terrace over the years, as changes in morphology, number, and location of their eruptive vents (Fig. 1.1a, b). Such changes are often associated with significant modifications in velocities and dynamics of pyroclast ejection (strongly influenced by vent geometry; Wilson et al. 1980; Ogden 2011), as well as in eruptive styles and intensities (Taddeucci et al. 2013a; Graettinger et al. 2015; Valade et al. 2016). Indeed, a highly variable behavior of the activity can be observed from the vents: for instance, at Stromboli the explosions occur sometimes radially, sometimes they form vertical or inclined jets, other times nearby vents erupt simultaneously (Fig. 1.1c–g). Detecting changes in vent

distribution and pattern of activity can lead to important insights into the shallow conduit system. However, direct observation of space-time vent migration at such volcanoes is still limited, and the relationship between this wide variety of output modes and the internal dynamics of the shallow conduit system remains to be understood.

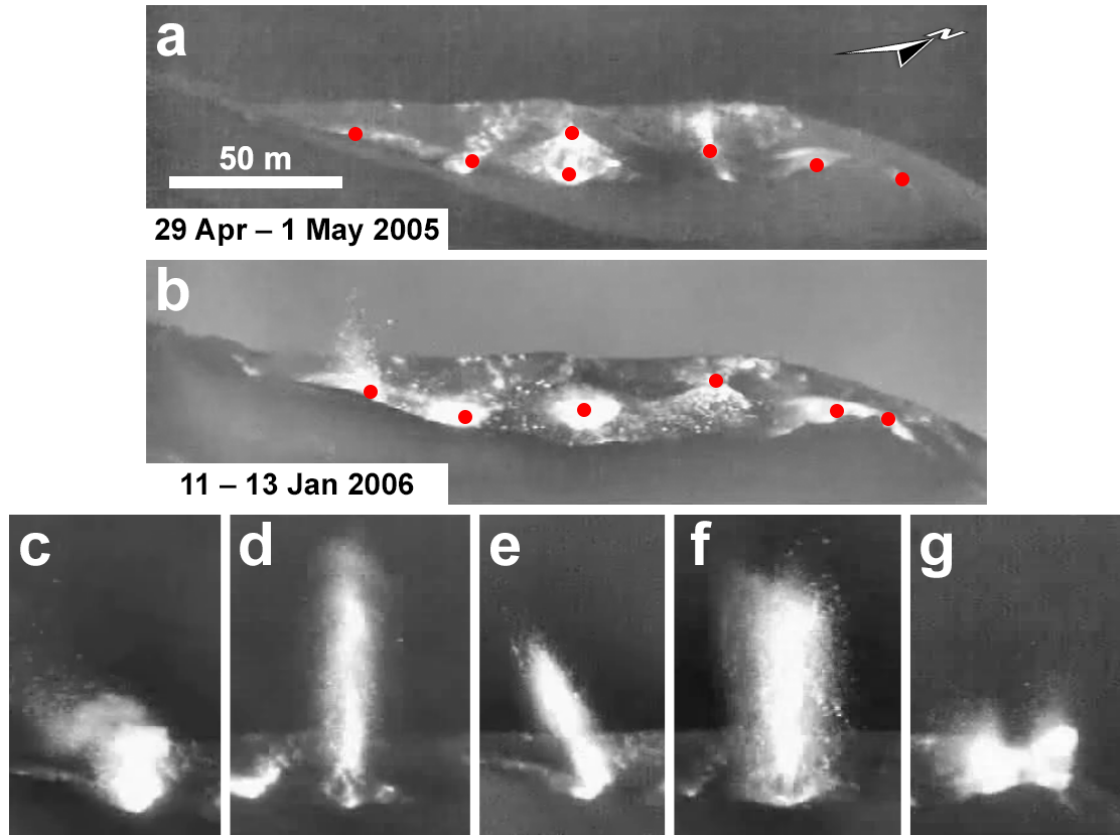


Fig. 1.1 **a** Location (red circles) of active vents within the crater terrace at Stromboli in 2005. **b** Location of active vents within the same crater terrace about one year later. Frequent, jet-like explosions of different shapes typically take place, for instance: **c** stubby; **d** tall and thin; **e** different angled; **f** tall and wide; **g** simultaneous between nearby vents.

Changes in pyroclast ejection are also due to an unobservable process of pyroclast acceleration occurring within the conduit and strongly induced by source parameters, such as depth where slug bursts (Taddeucci et al. 2002; Dürig et al. 2015; Taddeucci et al. 2017) or size and amount of pyroclasts (Bonadonna et al. 2012; Carcano et al. 2014). Up to now, although a large number of studies have addressed both the dynamics of this eruptive style and its products (e.g., Chouet et al. 1974; Blackburn et al. 1976; Weill et al. 1992; Ripepe et al. 1993; Vergnolle and Brandeis 1996; Seyfried and Hort 1999; Ripepe and Marchetti 2002; Dubosclard et al. 2004; Oppenheimer et al. 2006; Patrick 2007; Mori and Burton 2009;

Gouhier and Donnadieu 2011; Del Bello et al. 2012; Taddeucci et al. 2012a, b; Harris et al. 2012; Gaudin et al. 2014, 2017) and the modes of pyroclasts formation (i.e., the magma fragmentation, e.g., Alidibirov 1994; Alidibirov and Dingwell 1996a, b, 2000; Zimanowski et al. 1997; Papale 1999; Ichihara et al. 2002; Gonnerman and Manga 2003; Spieler et al. 2004a, b; Kueppers et al. 2006a; Mueller et al. 2008; Fowler et al. 2010; Stix and Phillips 2012; Richard et al. 2013; White and Valentine 2016), there is a slight number of studies focused on what happens to pyroclasts from the depth where a slug bursts to ejection from the vent.

The aim of my study is the definition of the relationships among the physical parameters inside the volcanic conduit and their influence on the modes of pyroclast ejection. Focusing on these relationships is fundamental in order to mitigate the associated hazards, bearing in mind that many people live close to, or closely approach for tourist reasons, these volcanoes. I used two separate yet fully complementary approaches to achieve this aim. First, I examined several surveillance videos concerning Strombolian activity, in order to analyze vent location and explosion parameters and characterize Strombolian eruptions in nature. Second, I simulated explosions through scaled laboratory experiments, in order to analyze the process of particle acceleration, which in nature is an unobservable process that influences the explosion parameters. This doctoral dissertation is a compilation of two manuscripts and is organized as follows.

“Chapter 2 – Parameterizing multi-vent activity at Stromboli Volcano (Aeolian Islands, Italy)” corresponds to Salvatore et al. (2018), a paper published in a scientific peer reviewed journal, which deals with the characterization of Strombolian eruptions in nature. In this paper, we provide a detailed database of Strombolian activity to highlight temporal changes of vent locations and activity styles at the Stromboli crater terrace. Our analysis is based on a dataset unique in the world, of more than 4000 events occurred in five 72-h-long time-windows between 2005 and 2009 and recorded by an infrared surveillance camera. In this work, I personally performed data interpretation and writing of the manuscript. Aurora Silleni, Davide Corneli, Danilo Bernini and I performed the video processing and the parameter extraction. Dr. Jacopo Taddeucci, Prof. Danilo M. Palladino, and Dr. Gianluca Sottili provided technical support for video processing and data interpretations. Dr. Daniele Andronico and Dr. Antonio Cristaldi provided and select the videos analyzed. All the co-authors also participated in manuscript preparation. Some modifications have been applied to the original manuscripts, such as the adaptation of the original format to this thesis layout and format, the incorporation of the electronic supplementary material within the text, and the addition of a part (section 2.2.5) from Salvatore et al. (2016), a poster I presented at the

“Ritmann Giovani Ricercatori” conference (Bari). Nevertheless, such modifications did not alter the conclusions reported in the original paper.

“Chapter 3 – Conduit pyroclast dynamics in Strombolian explosions in light of shock-tube experiments” corresponds to a manuscript in preparation and in part presented as an abstract (i.e., Taddeucci et al. 2018). In this work, we analyzed a series of laboratory experiments performed using the jet-burster, a transparent shock-tube in which a rapid decompression of a pressurized tube allows the release of particles. The experiments considered here are part of a dataset unique in the world, of 98 experiments (and a total of 196 videos) I performed in June-July 2016 and May 2018 and each recorded by two high-speed cameras. Our analysis is focused on the acceleration of these particles inside the shock-tube and their ejection, evidencing the effects of source parameters on the dynamics observed at vent. Several initial configurations (i.e., gas volume and pressure, particle size and amount, initial sample height from the exit, vent geometry) have been tested. In this work, I personally performed the video processing, the parameter extraction, the data interpretation and writing of the manuscript. Dr. Valeria Cigala, Dr. Jacopo Taddeucci, and I decided initial configurations and performed the experiments. Dr. Alejandra Arciniega-Ceballos took part directly in setup and performance of some experiments presented previously in Cigala et al. (2018). Dr. Juan José Peña Fernández supported on gas flow velocity calculation and provided the numerical gas jet simulations. All the co-authors assisted the data interpretations. Dr. Jacopo Taddeucci and Prof. Danilo M. Palladino participated in the manuscript preparation.

Both chapter 2 and 3 are subdivided in several subchapters as follows. Firstly, I introduce the treaty topic in each chapter. Secondly, I describe in detail the two methodologies used, i.e. (i) the analysis of vent position and activity styles over time on the terrace of the Stromboli crater for chapter 2, and (ii) the description and setup of the experimental apparatus and the dimensionless scaling analysis for chapter 3. Thirdly, I provide a complete overview of the results obtained. Fourthly, I discuss the significance and relevance of the results. Finally, I briefly summarize the important remarks.

Finally, “Chapter 4 – Concluding remarks” is a general summary of the two works, including implications for future studies.

As supporting information, a CD containing the following files is attached to this doctoral dissertation. The first folder “jet_burster” contains a selection of eight high-speed and high-resolution videos from our dataset, in order to enable readers to have access to dynamical features described in chapter 3. Every video is set to play at 25 frames per second.

The second folder “surveillance_images” contains all frames considered in chapter 2 and selected from original videos. The frames are divided for recorded day (labelled with the format “yyyy-mm-dd”), in turn divided for sample. Furthermore, this folder contains the poster Salvatore et al. (2016). Further data supporting this work (e.g., the full video dataset on jet-burster experiments) is available at the High Pressure High Temperature (HPHT) Laboratory of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome.

CHAPTER 2 – PARAMETERIZING MULTI-VENT ACTIVITY AT STROMBOLI VOLCANO (AEOLIAN ISLANDS, ITALY)

Valentino Salvatore^{1#}, Aurora Silleni^{1,2}, Davide Corneli¹, Jacopo Taddeucci³, Danilo M. Palladino¹, Gianluca Sottili¹, Danilo Bernini¹, Daniele Andronico⁴, Antonio Cristaldi⁴

correspondence to valentino.salvatore@uniroma1.it

1- Dipartimento di Scienze della Terra, Sapienza - Università di Roma, Piazzale Aldo Moro 5, Rome, Italy

2- Dipartimento di Scienze, Università di Roma Tre, Largo San Leonardo Murialdo 1, Rome, Italy

3- Istituto Nazionale di Geofisica e Vulcanologia, Sez. Roma1, Via di Vigna Murata 605, Rome, Italy

4- Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo, Piazza Roma 2, Catania, Italy

ABSTRACT The crater terrace of Stromboli Volcano (Italy) hosts several active vents which have evolved and migrated through time within three main vent areas: south-west (SW), central (C), and north-east (NE). Frequent, jet-like explosions typically take place, episodically interrupted by larger-scale paroxysms, which can substantially modify the morphology of the crater terrace and vent geometries. However, the link between the time-space evolution of vent activity and the shallow conduit system are still a matter of debate. In this work, we analyze the vent position and explosion parameters (jet duration and geometry) of 4296 events at Stromboli in five 72-h-long time-windows between 2005 and 2009, as recorded by an infrared surveillance camera. Vent locations illustrate the resilience of the shallow conduit system, which controls explosive activity at different time scales and depths. At the shallowest depth, where slugs burst, conduit branching and merging determines the evolution of simultaneous or alternating twin vents, while vent shape and slug size control local explosion parameters. These processes show variability on an hourly to daily time scale. Below the depth of the slug burst, the conduit system feeding each vent area controls which specific vent will host the explosions and also, possibly, the size of the slugs. Several observations suggest that the C and SW vent areas may be connected at this depth. The deeper conduit system, common to all vent areas, sets the overall explosion rate of the volcano and maintains a balance of this rate between the NE and the combined SW and C vent areas.

KEYWORDS Stromboli, Strombolian explosions, Crater terrace, Vent migration, Explosion parameters, Conduit system

2.1 INTRODUCTION

Open-vent volcanoes with persistent activity, e.g., Masaya (Nicaragua; Rymer et al. 1998), Etna (Italy; Cannata et al. 2011), Fuego (Guatemala; Waite et al. 2013), and Yasur (Vanuatu; Gaudin et al. 2014), are subject to continuous modifications in vent morphology, number, and position as a result of the interplay between eruptive styles and intensities (Spampinato et al. 2008; Calvari et al. 2014). Vent evolution and migration are critical for hazard assessment, as they are often associated with changes in eruptive mechanisms (Taddeucci et al. 2013a; Graettinger et al. 2015; Valade et al. 2016). Vent migration is usually inferred from eruptive sequences and the morphology of volcanic edifices in magmatic (Németh and Cronin 2011; Kereszturi et al. 2012), hydromagmatic (Sohn and Park 2005; Auer et al. 2007; Ort and Carrasco-Núñez 2009; Di Vito et al. 2011; Brenna et al. 2015; Pedrazzi et al. 2016), and mixed settings (Kósik et al. 2016). Previous studies on volcanic conduits are essentially based on field observations of partially eroded or exhumed volcanic edifices worldwide (e.g., Keating et al. 2008; Bosman et al. 2009; Geshi et al. 2010, 2011; Wadsworth et al. 2015). However, direct observation of space-time vent migration at mildly explosive, open-vent, active volcanoes is still limited. Thus, detecting activity shifts at multi-vent volcanoes can lead to important insights into the shallow conduit system, with implications for volcanic hazard assessment.

A well-known example is Stromboli, a composite stratovolcano located in the Aeolian Islands, between the southern Tyrrhenian Sea back-arc basin and the Calabrian Arc forearc region (Boccaletti et al. 1984; Peccerillo 2001; De Astis et al. 2003) (Fig. 2.1). The current eruptive activity at Stromboli, present for at least 1.3 ka (Rosi et al. 2000, 2013), is characterized by continuous degassing and weak Strombolian explosions from a crater terrace located at about 800 m a.s.l. (Marchetti and Ripepe 2005; Andronico et al. 2008, 2013; Taddeucci et al. 2013b).

Here, we provide a detailed database on Strombolian activity to highlight temporal changes of vent locations and activity styles at the Stromboli crater terrace by means of infrared surveillance camera images collected between 2005 and 2009. We track significant changes in vent distribution (i.e., stationary vs. migrating, nearing, merging) and patterns of activity (i.e., continuous vs. clustered, simultaneous vs. alternating at different vents, shifts

from one vent to another, eruptive hiatuses, explosion features). Different patterns are likely sourced at different depths in the conduit system.

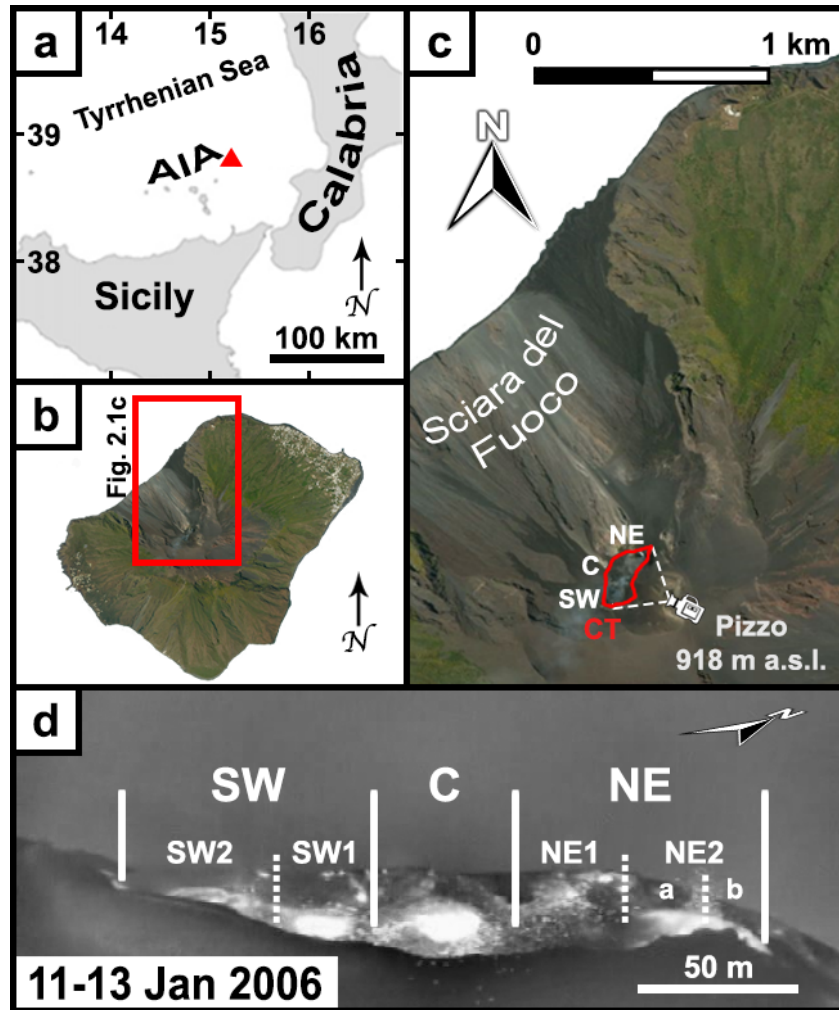


Fig. 2.1 **a** Location of Stromboli Volcano (red triangle) and the Aeolian Island Arc (AIA), Southern Italy. **b** Aerial view of Stromboli. **c** Zoom of **b** showing the vent areas (SW, south-west; C, central; and NE, north-east) within the crater terrace (CT, red line) and the location of the infrared camera on Pizzo. **d** Infrared camera still frame of the crater terrace, illustrating the vent nomenclature adopted in this study.

2.2 GEOLOGICAL SETTING

Persistently active explosive systems are characterized by frequent (intervals of seconds to minutes), impulsive (second-long) explosions that release coarse magma fragments and gases (Chouet et al. 1974; Parfitt and Wilson 1995; Ripepe et al. 1996; Oppenheimer et al. 2006; Houghton and Gonnermann 2008; Cashman and Sparks 2013; Gaudin et al. 2014; Taddeucci et al. 2015). In low viscosity basaltic systems, such activity has been attributed to the ascent and burst of large pressurized gas pockets through the magma column (i.e., *slugs*,

e.g., Blackburn et al. 1976; Sparks 1978; Jaupart and Vergnolle 1988; Parfitt 2004; Burton et al. 2007; Patrick et al. 2007; James et al. 2009; Chouet et al. 2010; Capponi et al. 2016). Changing rheological properties (viscosity, density), degassing and cooling conditions of magmas (Gurioli et al. 2014; Leduc et al. 2015) may lead to variations in explosion intensity and style (Lautze and Houghton 2005, 2007), with the typical occurrence of pulses and sub-pulses (Del Bello et al. 2015; Capponi et al. 2016).

At Stromboli, the *normal* explosive activity is episodically interrupted by higher intensity events (e.g., Rittmann 1931; Calvari et al. 2005; Barberi et al. 2009). In the last 25 years, these have been variably classified as *major explosions* and *paroxysms*, based on their increasing intensity (Barberi et al. 1993; Gurioli et al. 2013); *paroxysms*, regardless of intensity (Bertagnini et al. 1999); *small- to large-scale paroxysms* (Bertagnini et al. 2008; Landi et al. 2008; Métrich et al. 2010); and *violent Strombolian activity* (Valentine and Gregg 2008). More recently, Andronico and Pistolesi (2010) and Andronico et al. (2013) considered paroxysmal activity as part of a whole spectrum of eruption intensity within the ordinary Strombolian activity. Paroxysmal events may cause partial disruption of the vents, even up to the collapse of the whole crater terrace in the case of high-energy end-member events (e.g., Calvari et al. 2005; Rosi et al. 2006; Renzulli et al. 2009). The most recent event of this kind occurred during the February–April 2007 eruptive crisis (Barberi et al. 2009; Neri and Lanzafame 2009; Pistolesi et al. 2011; Andronico et al. 2013): effusive activity, fed by dikes branching from the main conduit, took place through ephemeral vents which opened on the NW volcano flank, causing the rapid subsidence of the summit crater terrace; a paroxysmal explosion occurred on March 15.

It is known qualitatively that the Stromboli crater terrace is affected by migration and evolution of eruptive vents, and their location, size, and geometry may change over the years. These changes, also induced by occasional paroxysmal explosions, make it difficult to identify individual vents (e.g., Calvari et al. 2005, 2010; Capponi et al. 2016); thus, most authors refer to craters or *vent areas*, each grouping a few active vents (e.g., Ripepe et al. 2005, 2009; Harris and Ripepe 2007a, b; Zanon et al. 2009; Taddeucci et al. 2013b; Gaudin et al. 2014). Historically, three main vent areas have been described at Stromboli, i.e., south-west, central, and north-east, hereafter SW, C, and NE, respectively (Washington 1917; Ripepe et al. 2005; Harris and Ripepe 2007a) (Fig. 2.1). These are consistently aligned along a SW-NE elongated trend (Rosi et al. 1980), explained by the stable location of a feeder dike, as suggested by seismo-acoustic data (Ripepe et al. 2001) and verified by seismic moment

tensor inversion (Chouet et al. 2003) and by analysis of thermal camera data (Ripepe et al. 2009).

2.3 METHODS

We analyzed thermal videos of Stromboli's crater terrace, recorded by a continuously operating surveillance camera belonging to Istituto Nazionale di Geofisica e Vulcanologia (INGV–Osservatorio Etneo). The camera was located at 918 m a.s.l. on Pizzo (or Sopra La Fossa; Fig. 2.1), facing the crater terrace about 150 m above and 240 m SE of the active vents. This infrared (8–14 μm band) camera (OPGAL EYE-M320B) is able to record volcanic activity continuously, where 320×240 pixel images were captured every 2 s. We thus kept record of all explosion occurrences, locations, and features within the limitation of the 2-s sampling rate (thus minor spattering events of <2 s duration were not captured) and 2-D perspective (which does not allow motion towards or away from the camera to be measured). The video dataset and processing methods described here follow, in part, those of Taddeucci et al. (2013b).

Attempts to apply a fully automatized analysis procedure yielded large uncertainty due to the intrinsic complexity of the image patterns. We had difficulty in distinguishing tephra emissions from gas plumes automatically using the color contrast provided by the infrared camera. Hence, the sampled videos were instead analyzed semi-automatically, trading a smaller sample size for more reliable results. From each video sampled, we extracted those frames capturing explosive activity at each vent. Then, after careful visual inspection, we identified a single frame for each explosion (hereafter the *representative frame*; Fig. 2.2a) in which a jet attains its maximum height before being dispersed. Subsequently, we processed each representative frame, separating the volcanic jet from the background (Fig. 2.2b), in order to remove all “hot spots” that interfered with the main event (e.g., hot pyroclasts on the ground near the vents). The processed frames were then analyzed using ImageJ (Abramoff et al. 2004), where we set a fixed brightness temperature threshold to define a jet area (Fig. 2.2c). We then fitted an ellipse to the selected area to extrapolate the explosion parameters, i.e., height (h), width (w), and ejection angle (a) of the jet (Fig. 2.2d). The first two parameters were obtained from the major and minor axes of the ellipse, respectively, and then converted to meters using the pixel size (0.87 m). Ejection angle is the angle from horizontal, measured counterclockwise, taking the major axis as the reference. Individual vents are often hosted within roughly circular depressions, i.e., *craters* (not to be confused with the vent

areas, which may or may not correspond to morphological depressions). The apparent (2-D) diameter (d) of vent-hosting craters was measured from the images when possible. When the crater rim was not directly visible, d was assumed to be equal to the maximum jet width at its lower point (Fig. 2.2a). Finally, we determined the adimensional aspect ratio ($A_r = h/w$) and the representative eruption duration (RED), i.e., the time in seconds elapsed from the first frame showing the onset of the explosion jet to the representative frame. The error for RED is ± 2 s, due to the camera frame rate; for h , w , and d , the measurement error is given by the pixel size (0.87 m), but the uncertainty may be up to a few meters in specific cases (e.g., for d when hot pyroclasts are present around the crater).

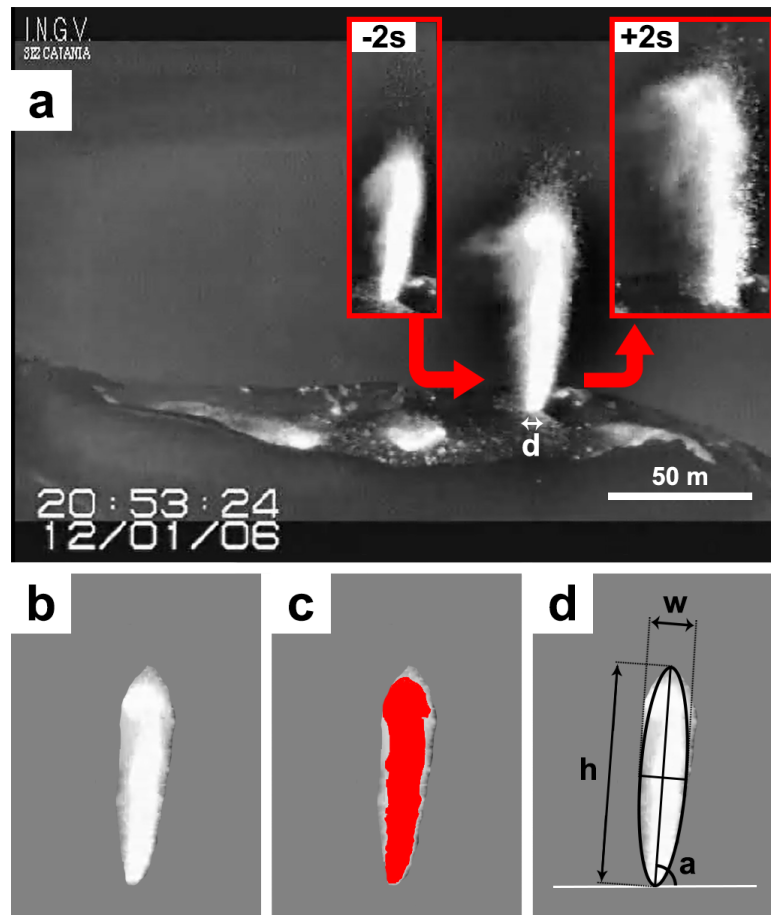


Fig. 2.2 **a** Typical representative frame from the infrared camera (time-stamped with the Coordinated Universal Time); d is the crater diameter as inferred from the same frame. In the red insets are the same jet 2 s (1 frame) before (on the left) and after (on the right) the representative frame. **b** The jet separated from the background. **c** Definition of jet area after setting a fixed brightness temperature threshold. **d** Height (h), width (w), and angle (a) of the jet calculated as the major and the minor axis of the best-fitting ellipse.

All videos were corrected for lens distortion, and, based on fixed reference points common to all videos, image analysis took into account shifts in the crater terrace field of

view due to relocation of the surveillance camera (e.g., following the 2007 eruptive crisis). For each explosion, we also recorded the location of the related source vent, i.e., the site where hot pyroclasts emerge from the ground.

Here, we focus on videos from the five consecutive years spanning 2005 through 2009. After a preliminary inspection of the whole period, a time-window of 72 consecutive hours was selected for each year based on: the occurrence of normal eruptive activity, good visibility (favorable weather conditions and an ash-free lens), and continuity of recording (without camera malfunctions and technical problems). In total, the five 3-day-long time-windows selected provided a total of 4785 recorded explosions (Table 2.1; Fig. 2.3). Considering the persistent occurrence of the present-day normal activity over at least 1.3 ka (Rosi et al. 2000) and self-similarity of the explosive events comprising normal activity (e.g., Harris and Ripepe 2007b; Patrick et al. 2007; Taddeucci et al. 2012a, 2013b; Bombrun et al. 2015), we are confident that our dataset is a representative sample of the behavior of multi-vent activity at Stromboli.

Table 2.1 Summary of the explosive events recorded during each 72-h-long time-window. Out of the 4785 recorded events, 4296 were analyzed to obtain explosion parameters (jet duration and geometry). For each case, we give the number of events analyzed and recorded.

Time-window	No. active vents	Total no. of events analyzed / recorded								
		All	SW3	SW2	SW1	C		NE1	NE2	
						a	b		a	b
29 Apr–01 May 2005	7	489 / 662		0 / 4	64 / 72	206 / 231	57 / 177	21 / 22	90 / 97	51 / 59
11–13 Jan 2006	6	1406 / 1465		385 / 393	53 / 56	189 / 192		633 / 641	86 / 94	60 / 89
20–22 Sep 2007	5	562 / 594		203 / 212	1 / 16	0 / 7		214 / 215	144 / 144	
07–09 Jul 2008	6	913 / 987	280 / 287	32 / 86	28 / 34	0 / 7		436 / 438	137 / 137	
19–21 Jul 2009	5	926 / 1077		232 / 300	312 / 387	0 / 7		202 / 202	180 / 183	
Total		4296 / 4785	280 / 287	852 / 995	458 / 565	452 / 617		1506 / 1518	748 / 803	

2.4 RESULTS

We provide here a detailed database of Strombolian activity, which covers multi-vent evolution and explosion features for the investigated time span. Hereafter, we refer to the 72-h time-windows for 2005, 2006, 2007, 2008, and 2009 as *sample-05*, *sample-06*, *sample-07*, *sample-08*, and *sample-09*, respectively. With regard to vent nomenclature, we label the three

main vent areas (SW, C and, NE) following previous literature (Ripepe et al. 2005; Harris and Ripepe 2007a; Gaudin et al. 2014). Within each area, individual vents are identified by a number which increases with increasing distance from vent area C. We also observed *twin vents*, i.e., close, coupled vents that erupted simultaneously (e.g., Chouet et al. 1974; Settle and McGetchin 1980; Capponi et al. 2016); these are distinguished by adding a letter after the vent number (e.g., vents NE2a and NE2b; Fig. 2.1d). Crater diameters (d) of the above-defined vents range from 3 to 23 m (Table 2.2).

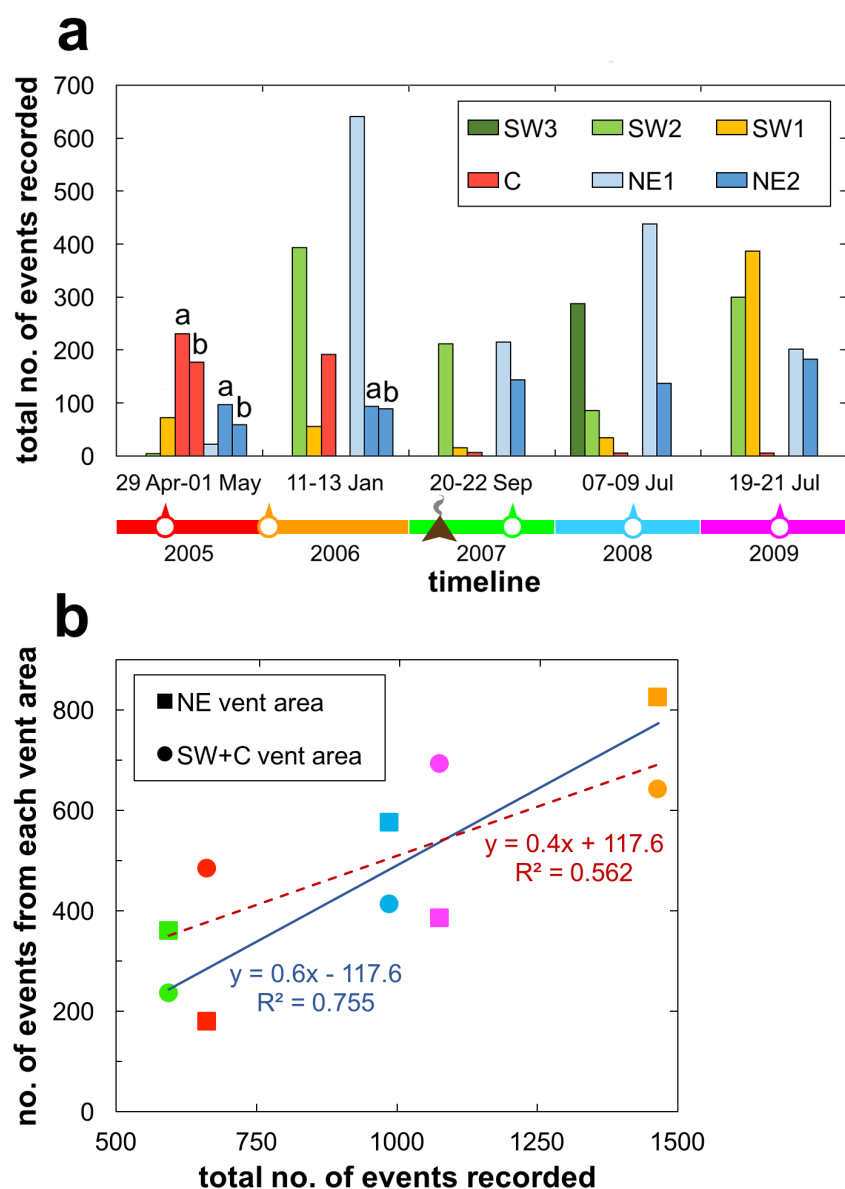


Fig. 2.3 a Total number of events recorded at Stromboli from each active vent during the five 72-h-long samples; twin vents are marked with *a* and *b* (data from Table 2.1). On the timeline, samples (circles) and the 2007 eruptive crisis (volcano symbol) are also reported. **b** Total number of events versus number of events from the NE (squares) and SW+C (circles) vent areas, for each sample. Solid and dashed lines represent linear fits for NE (blue line) and SW+C (red line) data, respectively. Color codes as per timeline.

Table 2.2 Estimated crater diameters for each 72-h time-window.

Sample	Crater diameter (m)							
	SW3	SW2	SW1	C		NE1	NE2	
				a	b		a	b
sample-05		8 ^a	12	11	9	5	11 ^a	21 ^a
sample-06		8 ^a	17		20	5	11 ^a	23 ^a
sample-07		20 ^a	6		11	16		5 ^a
sample-08	6	5	5		7	16		7
sample-09		9	21 ^a		3	15		12

The crater diameter uncertainly may be up to a few meters

^aHidden craters determined through jet width (see the “Methods” section)

2.4.1 EVOLUTION AND MIGRATION OF THE ERUPTIVE VENTS

Figure 2.4 reports the location of each vent in each 72-h time-window and their movement vectors in the crater terrace area over the 2005–2009 time span. Although the explosion frequency at individual active vents at Stromboli is highly variable (e.g., Carapezza et al. 2004; Andronico et al. 2008; Taddeucci et al. 2013b), we can confidently track each vent from one date to another, as supported by a quick video survey of the intervening periods. It appears that the vents occupied nearly constant locations across the crater terrace before the 2007 eruptive crisis (sample-05 and sample-06). After the 2007 crisis (sample-07), however, all vents migrated due to the partial collapse of the crater terrace in March 2007 (Calvari et al. 2010). Then (sample-08 and sample-09), all vents appeared to rise, concomitant with a gradual refilling of the crater terrace.

Twin vents tend to become less clearly separated over the years and eventually merge into a single vent at an intermediate position, as in the case of Ca-Cb and NE2a-NE2b twin vents which became the C and NE2 single vents, respectively (Fig. 2.4). A quick video survey revealed that activity intensified at the Ca vent after 27 December 2005, with strong explosions culminating in the disappearance of the Cb vent after 1 January 2006. From sample-07 to sample-09, a single C vent existed, but only with minor spattering activity.

Vent migration differed in the different vent areas. While the relative lateral position of the vents in the NE area did not change significantly from sample-05 to sample-09, vents in the SW area changed substantially in position and number (with the addition of vent SW3 in sample-08). The C vent mostly maintained its position, except for a shift towards the SW vent area in sample-09 (Fig. 2.4). Overall, vent migration seems to define two distinct, independent vent areas, persistent over time, rather than three as considered traditionally (e.g., Washington 1917; Ripepe et al. 2005; Harris and Ripepe 2007a; Gaudin et al. 2014), given the proximity of the C and SW vent areas.

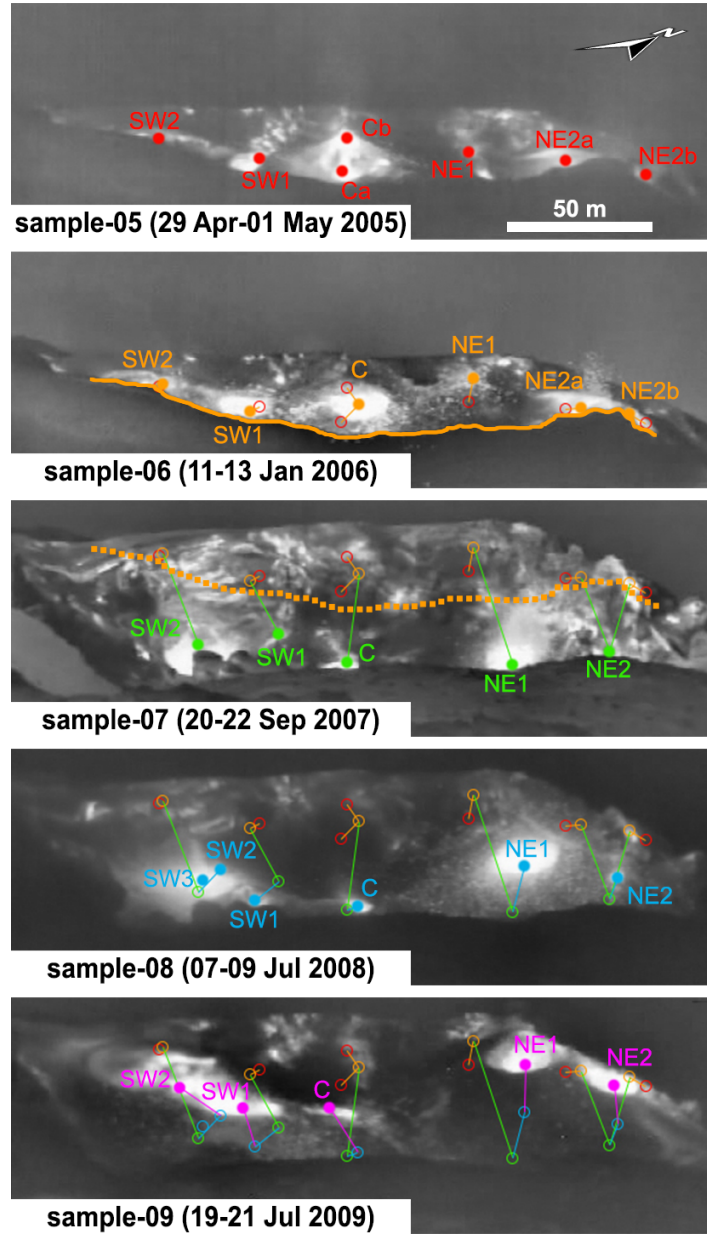


Fig. 2.4 Location (closed circles) and former position (open circles) of active vents at Stromboli and their movement vectors (lines) on the crater terrace over the five time-windows. The solid orange line marks the SE rim of the crater terrace as of January 2006; this is also superimposed (dotted line) over the collapsed crater terrace image of September 2007.

2.4.2 EXPLOSION FREQUENCY

The number of explosions recorded from individual active vents varied considerably between 4 (SW2, sample-05) and 641 (NE1, sample-06). The explosion frequency also varied within each 72-h time-window, as also did the distribution of explosions at the active vents (Table 2.1; Fig. 2.3). However, there was an overall waning in explosions between sample-07 and sample-09 (after the 2007 eruptive crisis) at the C vent area, with only puffing activity or

minor spattering occurring. In general, an increase in the total number of explosions at any specific vent area is accompanied by an increase in the explosion rate at all vent areas. By summing the explosions of the SW and the C vents areas, and performing a linear regression for the total number of explosions versus the number of explosions from NE and SW+C vent areas, we find that the two vent areas provided reciprocally between 40 and 60% of the total explosions (Fig. 2.3).

2.4.3 EXPLOSION FEATURES

Explosion parameters (h , w , A_r , a , and RED) for all individual explosions were measured over each of the five time-windows, with results varying at different temporal and spatial scales (Fig. 2.5; Table 2.3). Vent activity was either continuous or clustered into hourly intervals. For the twin vents, activity at Ca was almost continuous over the 3 days of sample-05, while simultaneous activity at its twin (Cb) was more limited. In sample-05 and sample-06, the activity was mostly alternating at NE2a-NE2b, with occasional simultaneous explosions.

Changes in explosion parameters consist of both gradual fluctuations and abrupt (within a few hours) shifts (Fig. 2.5). Similar changes in thermal signatures was showed among the NE and SW vent areas by Ripepe et al. (2005), who collected thermal data continuously over 4 days at Stromboli: events at the SW vent area were characterized by long lasting (>10 s), higher amplitude thermal signals with significant fluctuations, whereas events at the NE vent area were characterized by short (<5 s), impulsive, lower amplitude signatures. Harris and Ripepe (2007a) also noted abrupt shifts in puffing location. In our case, for example, in sample-09 at SW1, the ejection angle gradually increased until a shift occurred halfway through the 72-h period, concomitant with a hiatus in activity at vent SW2. After this point, SW1 showed more fluctuation in a , while at SW2, h and w became nearly constant. Similarly, in sample-06, SW2 and C experienced an abrupt and simultaneous shift in a after about 36 h, while at SW1 and SW2 h increased slightly before a near-steady phase during the final 36 h.

Furthermore, we noted alternating or specular behavior of parameters and/or activity within a single vent area. For instance, towards the end of sample-08, activity shifted first from SW3 to SW2 and then from SW2 to SW1; in sample-09 there was a synchronous increase in h at both vents in the NE vent area after about 30 h (Fig. 2.5). Shifts also occurred between the SW and C vent areas in sample-05, when activity alternated between SW1 and Cb, and in sample-06, where activity shifted between SW1 and C, being present for 1–12 h at

one location before shifting to the other (Fig. 2.5). While no simple relationships link the different parameters, we note that changes in h are paralleled by changes in A_r (but not in w) and a (e.g., sample-09). It appears that, in general, A_r increases with increasing h , pointing towards more collimated jets for higher explosions. In turn, more collimated jets show a smaller dispersion of a . This is consistent with, and supported by, Leduc et al. (2015).

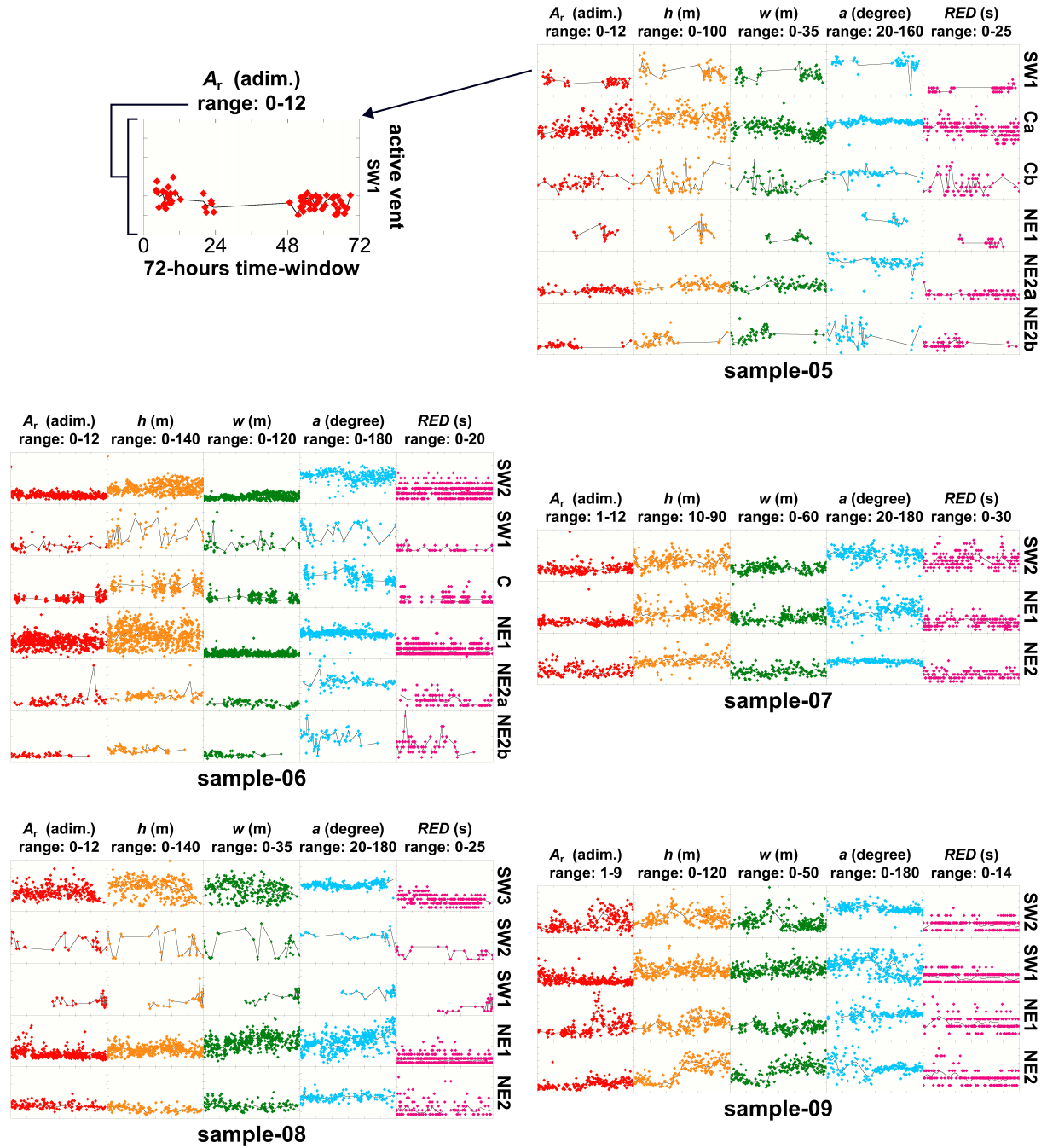


Fig. 2.5 Evolution of the explosion jet parameters during the five 72-h time-windows. A_r : aspect ratio; h : height; w : width; a : ejection angle; RED : representative eruption duration. The y-axis scale range varies from case to case and is reported at the top of each plot column. Enlarged versions of each time window plots are available in Appendix A.

Table 2.3 Range of variation and mean values of the explosion parameters for each active vent.

Explosion parameters	Sample	Range and mean							Total	
		SW3	SW2	SW1	C		NE1	NE2		
					a	b		a		b
A_r (adim.)	sample-05		Minor spattering	2-6 (3)	1-11 (5)	1-6 (4)	2-6 (4)	1-4 (3)	2-4 (2)	
	sample-06		1-9 (2)	1-5 (2)	1-5 (2)	0-10 (4)	1-11 (2)	1-3 (2)		
	sample-07		1-11 (3)	4 ^a	Minor spattering	1-10 (3)	2-7 (3)	1-11 (3)		
	sample-08	2-10 (5)	3-7 (5)	2-6 (3)	Minor spattering	2-10 (3)	2-6 (3)			
	sample-09		1-7 (3)	2-6 (3)	Minor spattering	2-9 (3)	1-6 (2)			
h (m)	sample-05		Minor spattering	24-84 (47)	12-94 (56)	12-80 (37)	16-71 (39)	18-53 (33)	13-63 (29)	
	sample-06		15-129 (44)	38-129 (72)	18-101 (58)	7-138 (64)	22-123 (40)	51-23 (34)		
	sample-07		19-68 (42)	71 ^a	Minor spattering	21-85 (44)	18-76 (47)	7-138 (47)		
	sample-08	14-137 (65)	9-99 (50)	17-98 (41)	Minor spattering	21-87 (47)	10-46 (27)			
	sample-09		21-113 (47)	21-101 (45)	Minor spattering	11-78 (42)	12-97 (53)			
w (m)	sample-05		Minor spattering	7-23 (14)	3-30 (12)	3-22 (10)	5-14 (9)	6-18 (12)	6-24 (13)	
	sample-06		5-32 (17)	7-101 (28)	9-53 (22)	5-49 (12)	4-31 (17)	9-28 (18)		
	sample-07		5-28 (15)	16 ^a	Minor spattering	8-57 (18)	5-30 (16)	3-101 (15)		
	sample-08	4-28 (5)	3-27 (11)	6-18 (13)	Minor spattering	4-33 (17)	4-18 (9)			
	sample-09		4-49 (15)	8-39 (19)	Minor spattering	4-27 (14)	5-48 (22)			
α (degree)	sample-05		Minor spattering	24-137 (109)	28-106 (90)	46-116 (89)	89-123 (107)	33-158 (126)	26-125 (75)	
	sample-06		21-143 (96)	33-129 (91)	47-168 (104)	11-136 (89)	33-175 (100)	23-164 (86)		
	sample-07		36-147 (103)	96 ^a	Minor spattering	28-165 (88)	76-172 (93)	11-175 (95)		
	sample-08	62-145 (102)	54-134 (104)	65-111 (88)	Minor spattering	31-174 (98)	55-125 (86)			
	sample-09		23-143 (100)	13-154 (81)	Minor spattering	18-153 (92)	29-163 (89)			
RED (s)	sample-05		Minor spattering	2-8 (3)	2-20 (9)	2-18 (7)	2-8 (4)	2-10 (4)	2-10 (5)	
	sample-06		2-12 (5)	2-6 (3)	2-10 (3)	1-10 (3)	2-10 (4)	2-18 (7)		
	sample-07		6-26 (13)	6 ^a	Minor spattering	2-14 (6)	2-14 (6)	1-26 (5)		
	sample-08	2-12 (6)	2-8 (4)	1-10 (4)	Minor spattering	2-14 (4)	2-20 (5)			
	sample-09		2-8 (4)	2-6 (3)	Minor spattering	2-12 (5)	2-12 (4)			

Values are represented as follows: min-max (mean)

^aIn sample-07 we analyzed only an explosion at the SW1 vent, omitting non-measurable, minor spattering

Generally, the frequency distribution of a (Fig. 2.6) is unimodal, and most jets appear to be, in 2-D projection, almost vertical. The modal distribution of a remains approximately constant from one sample to the next at each vent; exceptions are SW1, where a changed from $109^\circ \pm 14^\circ$ to $81^\circ \pm 32^\circ$, from sample-05 to sample-06, and NE1, where a changed from $107^\circ \pm 10^\circ$ to vertical in the same period. The bimodal distribution of a for NE2a and NE2b tends to converge from sample-05 to sample-06, and become unimodal in sample-07 when the twin vents merged at an intermediate position. Surveillance videos clearly show that a is independent of wind direction, the latter being clearly revealed by ash dispersion trends after the representative frame.

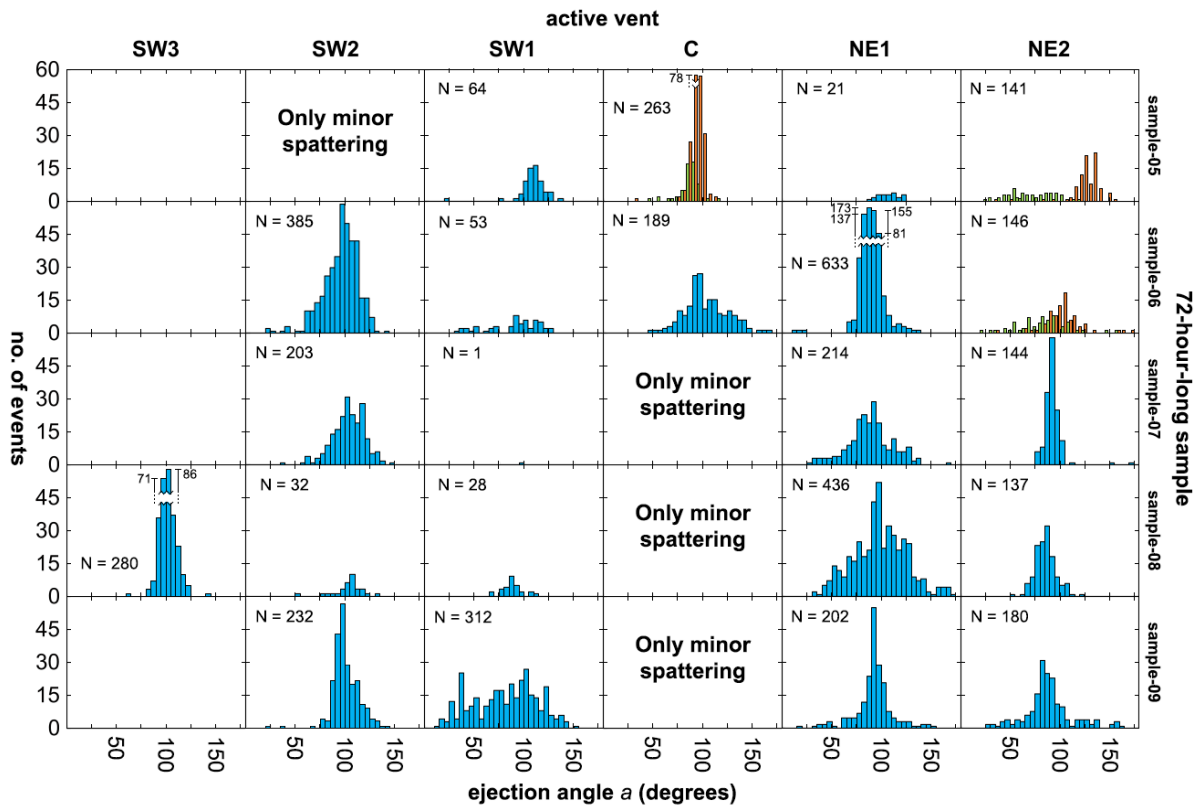


Fig. 2.6 Frequency histograms of ejection angle (a) for each active vent in each time-window. N, sum of the analyzed events for each vent. Bar colors are as follows: light blue, single vent; green, twin vent “a”; orange, twin vent “b”.

A direct relationship between the standard deviation of a and crater diameter can be observed (Fig. 2.7a). Considering all the time-windows and leaving out SW1 in sample-07 (in which we analyzed only one explosion), 16 out of 21 active vents show a suitable correlation between mean jet duration and mean jet height through the whole observation period (Fig. 2.7b; a summary of relations is reported in Table 2.4). This correlation is direct for 12 vents

and inverse for 4 vents, with direct correlations being stronger than inverse ones, with an overall trend of a longer duration for higher jets.

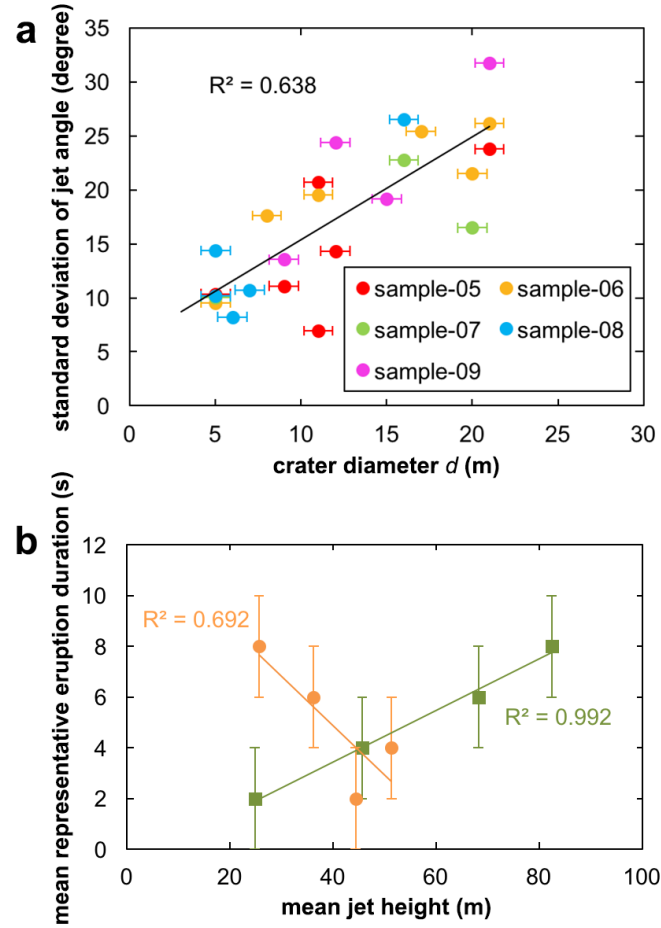


Fig. 2.7 **a** Standard deviation of jet angle, a measure of jet spreading angle, versus crater diameter; black line: linear regression fit. **b** Examples of direct (in green, SW2 vent in sample-08) and inverse (in orange, SW1 vent in sample-05) correlation between mean representative eruption duration and mean jet height; error bars are ± 2 s and ± 0.87 m. For full details on the relationships, see Table 2.4.

To provide a synoptic view of the explosion parameters and vent migration for all the samples, Fig. 2.8a plots the position of, and average explosion parameters h , w , and a associated with, each vent within each sample. We see that vent positions apparently cluster into two locations (SW+C and NE), rather than three areas (SW, C and NE), separated by a gap in the center-right part of the image (Fig. 2.8a) that remained free of active vents over the entire observation period. Also, explosions on the left (SW) of the gap tended to be preferentially oriented towards the SW, while they were mostly vertical to the right (NE). This vent gap and the different average orientations of explosions is even more apparent when

averaging together all explosions from each vent cluster (i.e., the NE and the SW+C vent areas) within each sample (Fig. 2.8b).

Table 2.4 Summary of correlations between mean RED and mean h , for each active vent (twin vents are grouped) per each sample. At SW2 in sample-05 and C from sample-07 to -09 there was only non-measurable, minor spattering; at SW1 in sample-07 we analyzed only a measurable explosion.

Sample	Active vent					
	SW3	SW2	SW1	C	NE1	NE2
sample-05			r (0.69)	d (0.92)	d (0.4)	d (0.85)
sample-06		d (0.85)	d (0.56)	r (0.34)	d (0.74)	r (0.62)
sample-07		d (0.02)			d (0.01)	d (0.5)
sample-08	d (0.87)	d (0.99)	d (0.07)		d (0.01)	d (0.29)
sample-09		d (0.31)	d (0.81)		d (<0.01)	r (0.46)

d : direct correlation, r : reverse correlation

The coefficient of determination are shown in brackets

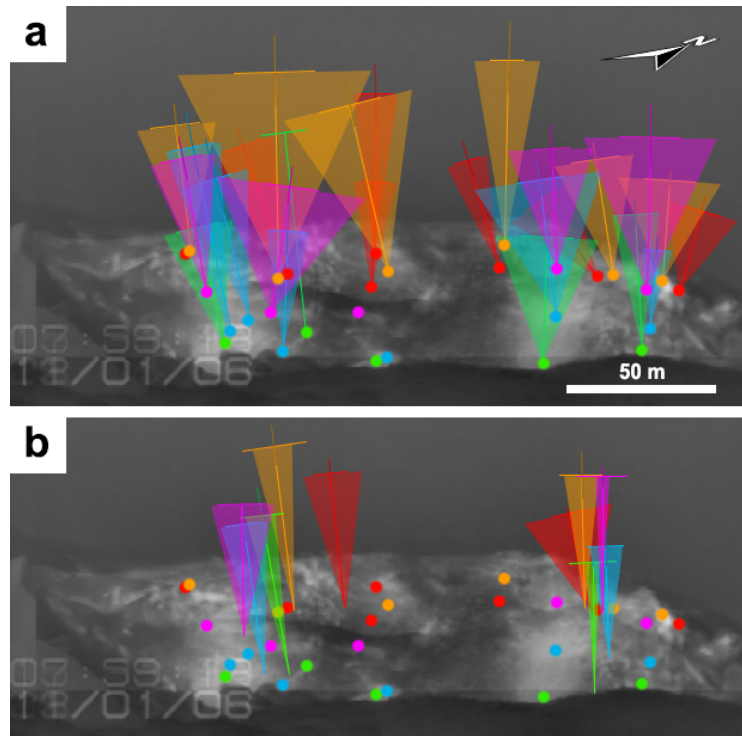


Fig. 2.8 **a** Representation of explosion parameters averaged for each individual vent within each sample. The thick line extending upward from each vent is the mean h with its standard deviation (thin line), the thick line perpendicular to mean h is the mean w , and the inclination of the mean h line is the mean a with its standard deviation (shaded area); dots without lines mark vents without measurable explosions (featuring only minor spattering or puffing activity, see Table 2.3). **b** Representation of explosion parameters averaged over the NE and the SW+C vent areas within each sample, with symbols located at the barycenter of the averaged vents. Colors are as follows: red, sample-05; orange, sample-06; green, sample-07; light blue, sample-08; violet, sample-09. The background image is a merge of images of the crater terrace from each of the five samples, after correction for camera displacement.

2.5 DISCUSSION

The vent dynamics we observed at Stromboli can be divided into two spatial and temporal scales (Fig. 2.9). The two spatial scales correspond to interplay at single/twin vents and shifts across whole vent areas. The two temporal scales correspond to variations over hours-to-days (inferred from our individual time-window observations) and months-to-years (inferred from sample-to-sample observations). Our grouping only applies to normal explosive activity.

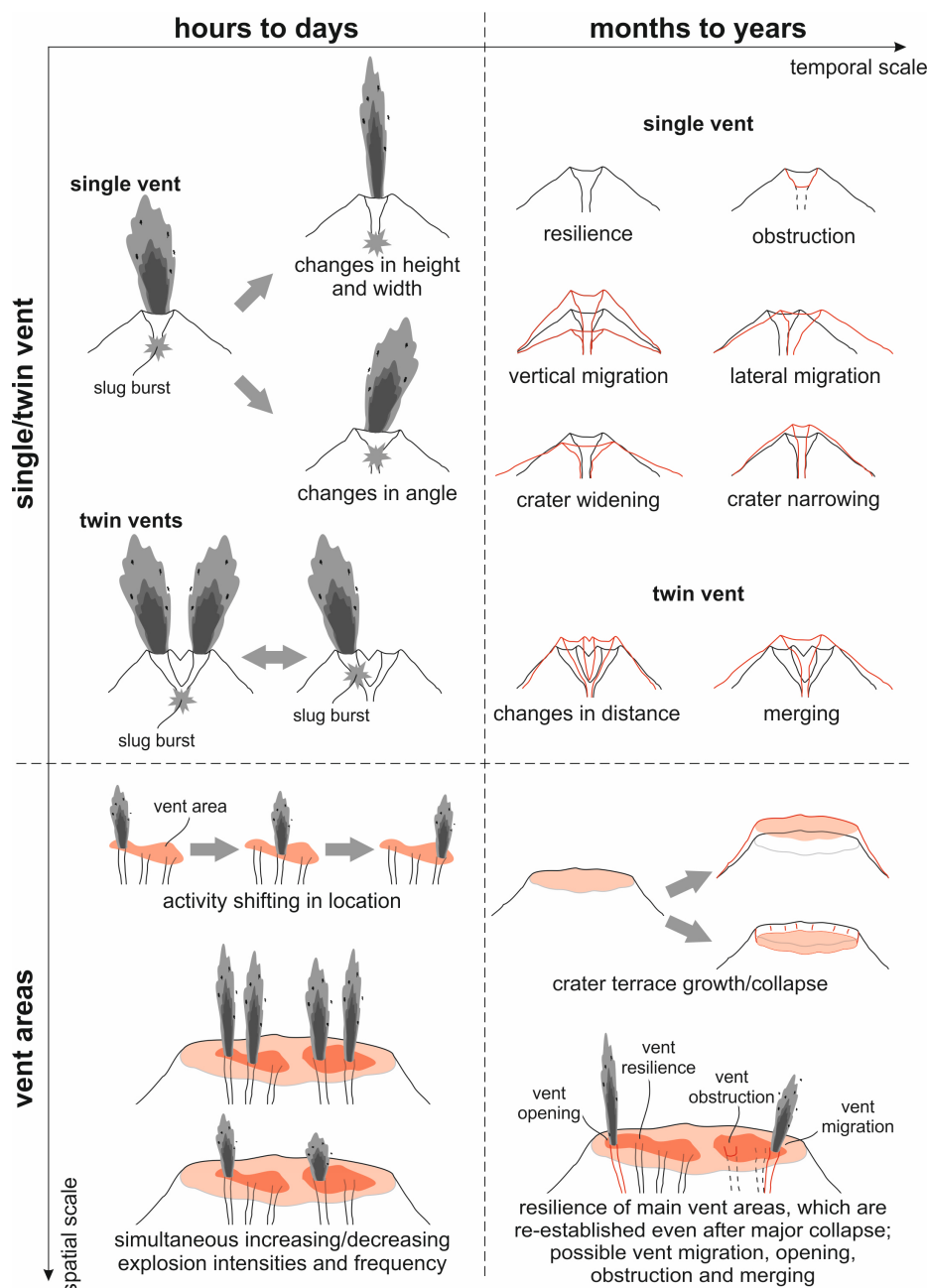


Fig. 2.9 The vent evolution and explosion properties recognized at Stromboli, developing over hours-to-days (within a sample) and months-to-years (from one sample to another) temporal scales. Subsequent geometries (red lines), crater terrace (light orange area), and different vent areas (dark orange area) are reported along with topographic profiles and supposed conduit locations.

2.5.1 SINGLE/TWIN VENTS: HOURS-DAYS

Here, we summarize and interpret the processes observed as occurring at a specific vent within our time-windows (i.e., over time scales of hours-to-days). These include systematic changes in explosion parameters and processes that drive cycles of simultaneous and alternating activity at twin vents. This time scale is considered to be suitable; given that weakly explosive activity at Stromboli has persisted since at least 1.3 ka (Rosi et al. 2000, 2013) in a manner that – based on measurements over the past four decades – means that eruption processes and properties extracted for periods of hours-to-days are quite comparable year-on-year and can be considered representative of the “typical” activity. Bombrun et al. (2015), for example, obtained a database of particle velocities and size distributions at Stromboli based on two measurement campaigns: in 2012, 8 h of recording was spread over 4 days, and in 2014, 8 h was recorded over 2 days, capturing a total of 31 eruptions. Extracted parameters compared well with studies made over similar time-windows since the 1970s (cf. Chouet et al. 1974; Ripepe et al. 1993; Ripepe 1996; Patrick et al. 2007; Delle Donne and Ripepe 2012; Taddeucci et al. 2012a; Gaudin et al. 2014).

Given our definition of h , i.e., the maximum height of a jet before becoming dispersed, the direct relation observed between the mean h and mean RED (Fig. 2.7b) suggests that, at many vents, increasingly large volumes of gas and magma are released through higher and longer-lasting explosions. This is in agreement with theoretical relationships between gas slug volume and overpressure (Del Bello et al. 2012). The lack of correlation and the less frequent, inverse relationship occasionally observed may be due either to vent shape factors (that, in some cases, became the dominant controlling parameter of pyroclast ejection, thus affecting the h - RED relationship) or could be the *type 0* events (i.e., tightly collimated gas-dominated jets poorly loaded in lapilli and bombs) observed by Leduc et al. (2015). In fact, the frequency distribution and standard deviation of a scales directly with the size of the crater: narrower craters host focused jets with an almost constant ejection angle, whereas relatively wider, flared craters host more variably oriented jets (Figs. 2.6, 2.7a, and 2.9; Table 2.1), possibly as a result of shallower explosions with lower aspect ratios and broader dispersal of the ejecta (Taddeucci et al. 2013a). This observation has implications for volcanic hazard assessment, since jet orientation (and the ensuing area subject to ballistic fallout) is less predictable in the latter case. Similarly, vent flaring by erosion may be responsible for an observed increase in w , while a decrease may be attributed to an increased depth of the slug burst. Asymmetric vent erosion is also a cause of gradual changes in a (e.g., vent NE1 in sample-08).

We infer that twin vents, erupting alternatively or simultaneously, share a common branching conduit: bursting of slugs at shallow levels (i.e., above conduit bifurcation) causes an explosion in only one of the twin vents, while deeper bursts (i.e., below conduit bifurcation) drive the fragmented magma through both conduits simultaneously (Fig. 2.9). Considering that slugs at Stromboli may burst at depths of between 0 and 100–150 m (e.g., Ripepe et al. 2001, 2002; Gurioli et al. 2013; Gaudin et al. 2014), conduit bifurcation for twin vents can be tentatively placed within this depth range.

2.5.2 SINGLE/TWIN VENTS: MONTHS-YEARS

Here, we describe those processes associated with the evolution of a specific vent within a persistent vent area, including vent migration and merging, over time scales of months-to-years. At Stromboli, cycles of vent formation, filling, and merging with stability of location of the vent areas are also recognizable. This can be seen, for example, on maps of the crater terrace between 1994 and 2004 (Harris and Ripepe 2007a, b) or images collected over the 2002–2004 (Patrick et al. 2007) and 2007–2012 (Calvari et al. 2014) time spans. In our study, except for vent resilience in a few cases (e.g., SW2 and SW1 between sample-05 and sample-06), all vents migrate vertically and/or laterally, some more than others. For instance, prolonged, asymmetric pyroclast accumulation resulted in migration (vertical and lateral) of vent C towards SW1 between sample-08 and sample-09 (Fig. 2.4), which could be linked to a preferential ejection of pyroclasts from C towards SW. Changes in crater size over time (Table 2.2; Fig. 2.4) are, instead, linked to changes in activity style, resulting from a competition between accumulation and removal of proximal pyroclasts by explosions. This is consistent with Patrick et al. (2007), which affirmed that a given vent normally maintains a particular eruption style and stability of its uppermost conduit on a shorter time scale (i.e., from days to weeks); besides, the presence and nature of a debris cover generated by fallback of pyroclasts into the vent and collapses of the conduit wall may modify explosion dynamics, magnitude, and pyroclast ejection velocity (Capponi et al. 2016).

Over this longer time scale, twin vents tend to widen and become progressively closer to each other with time (e.g., NE2a and NE2b between sample-05 to sample-06), eventually merging into a single vent at an intermediate position. Merging of twin vents can be facilitated by a strong explosion (e.g., the Ca-Cb to C transition from sample-05 to sample-06) or by subsidence due to crater terrace collapse (e.g., the NE2a-NE2b to NE2 transition from sample-06 to sample-07). In the case of the NE2a-NE2b merge, the bifurcation must

have been at a level higher than the post-collapse level, pointing to a depth of conduit bifurcation in this case of the order of a few tens of meters.

2.5.3 VENT AREAS: HOURS-DAYS

Here, we describe processes that occur at the spatial scale of vent areas and which may affect the simultaneous vs. alternating activity within a specific vent area (e.g., activity shifting from one vent to another). We also consider the simultaneous increasing/decreasing explosion intensities and frequencies over the whole crater terrace. Similarly, Ripepe et al. (2007) showed a puffing location which was stable at Stromboli over hour-to-day periods, which could shift with an abrupt transition from one vent area to another, while Ripepe et al. (2009) observed a migration of the activity from NE towards SW, probably due to magma drainage induced by the opening of an effusive fracture towards the NE.

We observe alternating or parallel activity at adjacent vents of a certain vent area, pointing to a link between these vents deeper than the depth of slug burst, which seems to control not only the location of explosive events (e.g., the migration of activity from SW3 to SW2 to SW1 in sample-08) but also the explosion parameters within a specific vent area. For example, the increasing h and the abrupt shift in a that occurred simultaneously at SW2 and C in sample-06, as well as at SW1 and Ca-Cb in sample-05, were not paralleled at the NE vents. These changes at the scale of vent area suggest that deeper-seated functions the conduit system, such as depth of slug formation and deeper conduit geometry (James et al. 2004; Chouet et al. 2008; Taddeucci et al. 2013b), might also play a role in shaping explosive activity. The depth of interest could be tentatively located between 220 and 275 m below the crater terrace, consistent with the most common location of the source of very long period (VLP) seismic events at Stromboli (Chouet et al. 2003; Marchetti and Ripepe 2005; Leduc et al. 2015). However, the depth of this seismic source is not stable over time along the conduit but largely varies in height with the magma column height (Marchetti and Ripepe 2005; Ripepe et al. 2015; Valade et al. 2016). This means that the depth of slug formation can vary, and this has been shown to control patterns of activity in the vent areas (Taddeucci et al. 2013b).

We also observe changes in the explosion parameters that are concomitant at all vent areas, as in the case of the simultaneous increase in h at all vents in sample-09. Such changes point to an even deeper control factor (or factors) that has been linked to the overall gas/magma input by Aiuppa et al. (2009) and Ripepe et al. (2009). This results in a variation that is common to all vent areas and sets the overall eruption rate of the volcano, which is

(roughly) equally distributed among the different vent areas (Fig. 2.3b). More generally, these factors may control the simultaneous increase in the frequency and intensity of explosions over the years (Andronico et al. 2008; Ripepe et al. 2009; Taddeucci et al. 2013b). This deeper control factor may reside in either the intermediate magma reservoir located at 3–3.5 km in depth, or the deep source of gas-rich magma at 7–9 km, where deep-rooted paroxysmal eruptions also originate (Vaggelli et al. 2003; Francalanci et al. 2004, 2005; Landi et al. 2009; Métrich et al. 2010).

2.5.4 VENT AREAS: MONTHS-YEARS

At the time scale of months-to-years, we observe resilience of the main vent areas, in spite of changes at the vent scale, and the growth versus collapse of the crater terrace. Similarly, Harris and Ripepe (2007b) showed a resilience of the two systems (NE and SW), whose vent areas were re-establishing after the 2002 collapse (e.g., Bonaccorso et al. 2003; Calvari et al. 2005; Marchetti and Ripepe 2005). In our case, after the 2007 collapse (sample-07), all vents were relocated to a lower elevation within the collapsed area with consequent effects at vent scale (e.g., merging of NE2a and NE2b, whose conduit bifurcation had been above the level of collapse; Fig. 2.4). Indeed, the accumulation of pyroclasts from sample-07 to sample-09 shifted all vents upward, especially those of the more active NE vent area, as the floor of the crater terrace was built-up following the collapse in 2007 (Rosi et al. 2013). Despite the 2007 collapse, the resilience of the main vent areas is nevertheless clear in Fig. 2.4, accentuated by the growth of the crater terrace between sample-07 and sample-09.

The active vent locations at Stromboli that had been essentially stable between sample-05 and sample-06, were influenced by the 2007 eruptive crisis in different ways depending on their location. While vent NE1 maintained its location, vent re-distribution occurred in the SW area (Fig. 2.4). It may mean that the system of the NE vent area (few conduits with few shallow bifurcations) is simpler and more resilient than the system of the SW vent area (a complex shallow bifurcation system). Likewise, from maps in Harris and Ripepe (2007a, b) the NE vent area always seems to re-establish its two vent system, whereas the SW vent area is often a wide collapse depression with vents scattered across it. Similarly, the 2002 collapse produced significant changes in the vent distribution within the crater terrace where, likewise, NE1 maintained its identity but the SW crater underwent a re-distribution (Harris and Ripepe 2007a, b).

Several lines of evidence suggest that the SW and C vent areas may be linked at a relatively shallow level (i.e., above a depth of 220 to 275 m below the crater terrace, as argued

above). First, the simultaneous paucity of activity at the SW1 and C vents in sample-07 is indicative of a common source that was affected by the 2007 collapse (Table 2.2); second, the alternating activity and the synchronous changes in explosion parameters observed at specific vents of SW and C areas (e.g., SW1 and Cb in sample-05 and SW2 and C in sample-06; Fig. 2.5); third, the similar increase in explosion frequency and intensities in the NE and combined SW and C areas (Fig. 2.3b); and finally, the pattern of vent location and jet ejection angles of the two vent areas (Fig. 2.8). Furthermore, indirect support to a link between the SW and the C vent areas is provided by direct observations of the crater terrace in May 2016 (Fig. 2.10) and June 2017, where a wide, common collapse depression affected the area formerly hosting the SW and C vents. Towards the surface, SW and C vent areas formed discrete entities with different styles (i.e., C typically produced puffs and rare explosions, due to its being more central to the dyke system; Landi et al. 2011). In this scenario, all vent areas are linked at depth, but the conduit system of the NE vent area bifurcates off at greater deep from SW-C system (i.e., below the level at 220–275 m), whereas C system bifurcates from SW quite close to the surface (i.e., within the level at 220–275 m).

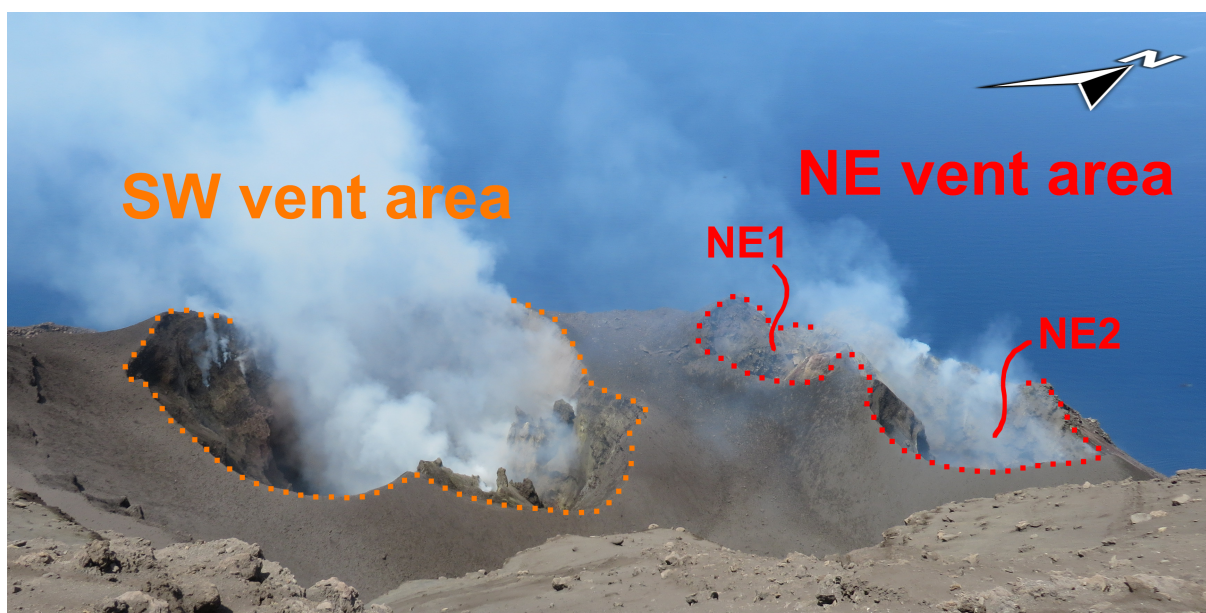


Fig. 2.10 Stromboli crater terrace viewed from Pizzo in May 2016. A wide, common collapse depression affects the area formerly hosting the SW and C vents. The SW (orange dotted line) and NE (red dotted line) vent areas are divided by a vent gap in the center-right part of the image.

Previous studies report an increase in the number of explosions for at least a few months before the 2007 eruptive crisis (Ripepe et al. 2009; Calvari et al. 2010; Andronico et

al. 2013). During this time, there were > 10–15 explosions per hour on average and peaks of up to 25 explosions per hour (Andronico et al. 2008). With regard to the periods investigated here, we observe the highest number of explosions in sample-06 (Fig. 2.3). Following this, the lower frequency of events recorded in sample-07 is part of the gradual renewal of normal Strombolian activity following the eruptive crisis (Aiuppa et al. 2009; Inguaggiato et al. 2011).

2.5.5 HYPOTHETICAL SCHEME OF THE SHALLOW CONDUITS

In light of explosion features and location of active vents, we propose a hypothetical scheme, or structure, of the shallow conduit setting of Stromboli over the five time-windows (Fig. 9), showing the resilience of the shallow conduit system at timescale from hours to years and through the occurrence of a significant eruption crisis.

In sample-05 (29 April–1 May 2005), the SW1 vent was likely linked with the twin C ones, while the SW2, producing only 4 weak explosions, is not considered here. In the NE vent area, the NE1 vent appeared quite tilted, while the twin NE2a and NE2b shallow conduits converged at shallow depth. In sample-06 (11–13 January 2006) few changes occurred since 2005, except for a more vertical setting of the NE1 conduit, possibly due to cone growth, and the collapse of the area interposed between Ca and Cb vents, resulting in a single, relatively wide vent. The twin NE2a and NE2b become progressively closer to each other respect to the previous year. In sample-07 (20–22 September 2007), after the eruptive crisis all vents were relocated at lower elevation within the collapsed area. As a result, first, the bifurcation below SW1 and C vents was closer to the surface with respect to previous years; second, the exposure of the deeper part confirmed that NE1 conduit was quite tilted; and finally, the merging of the NE2a and NE2b suggests that the original bifurcation was at a level higher than the post-collapse one. In sample-08 (07–09 July 2008), pyroclast accumulation shifted upward all vents, especially those of the more active NE vent area, also setting the conduits more vertically. In this case, the SW1 vent was probably originated by a new SW2-SW3 branch, as suggested by related mean a values (Fig. 2.8a, Table 2.3).

In sample-09 (19–21 July 2009), the continuous growth by pyroclasts accumulation resulted in migration of the C vent closer to the SW vent area, thus delineating at the best the NE and SW+C bipartition.

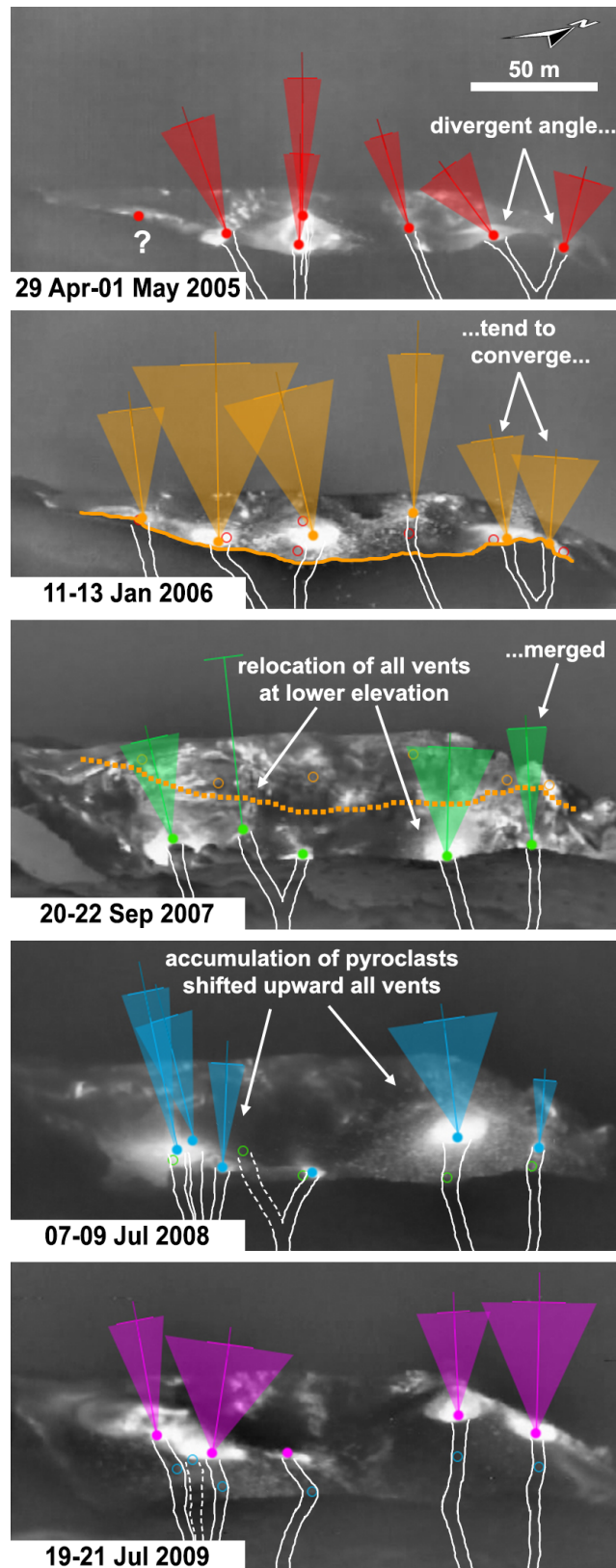


Fig. 2.11 Sketch of the hypothetical shallow conduit setting (white lines) over the five time-windows. Locations (closed circles) and former positions (open circles) of active vents at Stromboli are also shown, as well as the representation of explosion parameters averaged for each individual vent within each sample (see Fig. 2.8a for graphical details). Dotted white lines in July 2008 and July 2009 are the former SW1 and SW2 conduits, respectively. The solid orange line marks the SE rim of the crater terrace as of January 2006; this is also superimposed (dotted line) over the collapsed crater terrace image of September 2007.

2.6 CONCLUSIONS

Our analysis of the Stromboli multi-vent system and explosion jet dynamics is based on 4296 (out of 4785) events from 72 consecutive hours of observation for each year during the 2005–2009 period. When set in the context of other published data sets covering short (hour-to-day) and longer (month-to-year) periods, we find that sampling provides a detailed database that is representative of normal activity at Stromboli.

Our observations highlight changes in explosion parameters and locations of active vents at different time-scales, i.e., from hours-to-days to months-to-years. Over the short time scale we essentially track systematic changes in the activity style (e.g., jet parameters, explosion intensity and frequency), whereas over the longer time scale, we track the evolution of individual vents and vent areas, including vent migration and merging, and subsidence of the whole crater terrace followed by re-establishment of vent zones. Over our study periods, several lines of evidence suggest a dual behavior of the crater terrace, with the NE vent area operating independently of the joint SW+C areas, although deeper system changes drive changes that affect all three areas.

We can broadly infer a hierarchy of depths in the conduit system that controls the explosive activity at Stromboli. At the shallowest depth (<150 m), slug size, conduit geometry and vent shape control local explosion parameters, while possible conduit branching may determine the simultaneous versus alternating activity at twin vents. At a deeper level (possibly at around 220–275 m below the crater terrace, i.e., at the level of the VLP), the conduit system geometry, level of free surface, and precise location of the VLP determine which specific vent will host the explosions and also some more general explosion features within a vent area (the C and SW vent areas may be linked above this depth). At the deepest level, common to all vent areas (tentatively identified as the magma reservoirs at 3–3.5 km or at 7–9 km of depth), the features of the conduit system set the overall level of activity with increases and decreases in activity being roughly balanced across all vent areas (NE and SW+C).

Dynamics of vent evolution and explosive behavior at Stromboli may provide basic inferences on the geometry and dynamics of conduit systems at different time and depth scales. This may hold for other persistent multi-vent systems worldwide, such as Masaya (Nicaragua), Pu'u 'O'o (Hawaii), Etna (Italy), Fuego (Guatemala), and Yasur (Vanuatu) (e.g., Rymer et al. 1998; Marchetti and Harris 2008; Cannata et al. 2011; Waite et al. 2013; Gaudin et al. 2014). Our results also have implications for volcanic hazard assessment, since the

observed patterns of temporal changes in explosion parameters (such as jet orientation, height, and width) and source vent distribution can be used, for example, to define areas prone to ballistic dispersal and variations in their location.

2.7 ACKNOWLEDGEMENTS

We acknowledge Karoly Németh and two anonymous reviewers, as well as the handling editor (Josef Dufek) for the helpful comments that significantly improved the manuscript.

2.8 FUNDING INFORMATION

This work was partially funded by the Italian “Dipartimento della Protezione Civile” in the frame of the 2007–2009 Agreement with Istituto Nazionale di Geofisica e Vulcanologia – INGV (Project V2 “Paroxysm”).

CHAPTER 3 – CONDUIT PYROCLAST DYNAMICS IN STROMBOLIAN EXPLOSIONS IN LIGHT OF SHOCK-TUBE EXPERIMENTS

Valentino Salvatore^{1#}, Valeria Cigala², Jacopo Taddeucci³, Alejandra Arciniega-Ceballos⁴, Juan José Peña Fernández⁵, Damien Gaudin², Danilo M. Palladino¹

correspondence to valentino.salvatore@uniroma1.it

1- Dipartimento di Scienze della Terra, Sapienza - Università di Roma, Piazzale Aldo Moro 5, Rome, Italy

2- Department für Geo- und Umweltwissenschaften Sektion Mineralogie, Petrologie und Geochemie, Ludwig-Maximilians-Universität München, Theresienstraße 41, München, Germany

3- Istituto Nazionale di Geofisica e Vulcanologia, Sez. Roma1, Via di Vigna Murata 605, Rome, Italy

4- Instituto de Geofisica and Instituto de Geologia, Universidad Autonoma de Mexico, Mexico City, Mexico

5- Technische Universität Berlin, Straße des 17. Juni 135, Berlin, Germany

ABSTRACT Through a Strombolian eruption, a mixture of gas-pyroclasts is ejected into the atmosphere. Velocities and dynamics of pyroclast ejection, which a large number of studies is focused on, show significant changes as a function of several factors, such as the depth from which pyroclasts are released and their ascent in the conduit (acceleration, velocity, collisions, degree of coupling with the gas). Dealing with these slight-studied, unobservable processes occurring in the conduit is crucial to understand the relationship between pyroclast rising in the conduit and their output parameters at the vent (velocity, angle ejection, etc.). Here, we investigate the ejection of a non-coupled (Stokes number $\gg 1$) gas-particle mixture in light of analogue experiments by means of a transparent shock-tube. We recorded the entire path of the particles by high-speed cameras, testing several initial configurations (i.e., gas volume and pressure, particle size and amount, initial sample height from the exit, and vent geometry). These experiments reveal a particle acceleration-deceleration phase in the conduit that influences the pyroclast ejection velocity at the exit in function of the initial conditions. Furthermore, in our experiments, we tested an empirical model previously applied to volcanic eruptions to compute the depth from which pyroclasts are released. We found that the aforementioned model underestimates or overestimates depth values, the error being higher at lower initial energy and with a sample more distant from the exit. These results, compared to

actual Strombolian explosions, open the way for potential, new inferences on the processes controlling the dynamics of pyroclasts during low-scale explosive eruptions.

KEYWORDS Strombolian explosions, jet-burster, shock-tube, pyroclast ejection, pyroclast acceleration

3.1 INTRODUCTION

Strombolian eruptions are typically characterized by frequent (intervals of seconds to minutes) and impulsive (second-long) releases of pyroclasts of different sizes and gases into the atmosphere (Chouet et al. 1974; Schmid 1981; Parfitt and Wilson 1995; Oppenheimer et al. 2006; Cashman and Sparks 2013; Gaudin et al. 2014; Taddeucci et al. 2015), due to the ascent and burst of large pressurized gas pockets (i.e., *slugs*) through the magma column (Blackburn et al. 1976; Sparks 1978; Jaupart and Vergnolle 1988; Seyfried 1997; Chouet 2003; Johnson 2003; James et al. 2004; Parfitt 2004; Burton et al. 2007; James et al. 2008; Kremers et al. 2013; Capponi et al. 2016). During each explosion, multiple, second- and sub-second-lasting ejection of pyroclasts with velocities decreasing over time occur, defining *pulses* and *sub-pulses*, respectively (Taddeucci et al. 2012a; Gaudin et al. 2014; Bombrun et al. 2015; Del Bello et al. 2015; Capponi et al. 2016). Up to now, numerous works focused on this eruptive style, aiming to either examining the pyroclast velocity and ejection into the atmosphere (e.g., Weill et al. 1992; Seyfried and Hort 1999, Dubosclard et al. 2004; Gouhier and Donnadieu 2011; Taddeucci et al. 2012a; Harris et al. 2012, Gaudin et al. 2017) or estimating the mass and pressure of the driving gas phase (e.g., Chouet et al. 1974; Blackburn et al. 1976; Ripepe et al. 1993; Vergnolle and Brandeis 1996; Ripepe and Marchetti 2002; Mori and Burton 2009).

Remarkably, pyroclast ejection shows significant changes in observed velocities and dynamics, being strongly influenced by initial conditions, such as depth where slug bursts (Taddeucci et al. 2002; Dürig et al. 2015; Taddeucci et al. 2017), size and amount of particles (Bonadonna et al. 2012; Carcano et al. 2014), and vent geometry (Wilson et al. 1980; Ogden 2011). Therefore, a key point is to relate exit parameters determined at vent to the controlling eruption source conditions. However, it is very arduous to obtain clear information about the eruption source conditions exclusively by observing the typical explosive manifestations of the Strombolian eruptions occurring in nature.

Useful to link observations and control parameters is the comparison of experimental data directly acquired from real eruptive events to those obtained by scaled experimental tools which reproduce the explosions. The advantage of this investigation technique is the possibility of setting many input parameters, focusing on simpler processes and specific conditions without considering natural complexities. A well-known example of these tools is the *fragmentation bomb* (Alidibirov and Dingwell 1996a, b; Spieler et al. 2004a, b; Kennedy et al. 2005; Mueller et al. 2005; Kueppers et al. 2006a, b; Scheu et al. 2006; Alatorre-Ibargüengoitia et al. 2010, 2011; Cigala et al. 2017), a shock-tube consisting of a pressurized steel autoclave (that mimics a volcanic conduit), which releases gas and particles to a huge tank at atmospheric conditions when depressurized.

Pyroclast ejection is an observable result of hidden processes of pyroclast formation (i.e., magma fragmentation) and their ascent in the conduit (Dubosclard et al. 2004; Gouhier and Donnadieu 2011; Taddeucci et al. 2012a). Although large number of studies have addressed the magma fragmentation (e.g., Alidibirov 1994; Alidibirov and Dingwell 1996a, b, 2000; Zimanowski et al. 1997; Papale 1999; Ichihara et al. 2002; Gonnerman and Manga 2003; Spieler et al. 2004a, b; Kueppers et al. 2006a; Mueller et al. 2008; Fowler et al. 2010; Stix and Phillips 2012; Richard et al. 2013; White and Valentine 2016), there is a slight number of studies focused on pyroclast ascent in the conduit (i.e., from their generation where slug bursts to their ejection from the vent). For instance, a great limitation of the fragmentation bomb is that processes occurring inside the steel autoclave cannot be observed, and that the flow is almost unconfined outside of the pressurized section. Focusing on these hidden processes (e.g., acceleration and velocity of the particles and their coupling with the gas) associated to source parameters is an important target, since they are a control factor of the eruptive dynamics observed in nature (e.g., particle velocity and ejection angle; Houghton et al. 2004; Kennedy et al. 2005; Pioli et al. 2009), and have strong implications for volcanic ballistic hazards assessment.

Moreover, it is crucial to estimate the fragmentation level (i.e., depth of the free magma surface), since it controls pyroclast ejection (Taddeucci et al. 2002; Dürig et al. 2015; Taddeucci et al. 2017) and their textural properties (e.g., vesicularity and size; Gardner et al. 1996; Dufek et al. 2012). Previous attempts based on petrographic analysis (Gardner et al. 1996), numerical modelling (Polacci et al. 2004), and geometrical reconstructions (Dürig et al. 2015). Laboratory experiments may help constraining this estimation better. Investigating nonlinear particle velocity decay over time obtained from fragmentation bomb experiments, Alatorre-Ibargüengoitia et al. (2010, 2011) developed an empirical equation:

$$v_p = \frac{v_{max}}{1 + \frac{v_{max}}{h} t}, \quad (1)$$

where v_p is the velocity of the particles, v_{max} is the maximum ejection velocity measured at the observation point, t is the time and h is the vertical distance from the base of the sample in the apparatus to the observation point. This equation bears on the following assumptions: i) pseudo-gas behavior of the gas-particle mixture; ii) initial uniform density of the mixture in the conduit; iii) the viscosity, wall friction and weight of the mixture, as well as the heat conduction, can be neglected (Turcotte et al. 1990; Woods 1995); iv) constant mass of the mixture; v) cylindrical conduit; vi) constant v_{max} of the mixture in the conduit, following the initial acceleration; vii) non-choked flow conditions. Strombolian eruptions recorded by high-speed cameras reported a nonlinear decay trend of the velocities over time, which is well-approximated by equation (1) (Taddeucci et al. 2012a, b). Gaudin et al. (2014) estimated the depth of pyroclast release for Strombolian eruptions by means of a resemble calculation of h , although most of their obtained values closely match the estimation of Taddeucci et al. (2012b). Nevertheless, it is still unclear what h actually represents: for several eruptions occurred at Stromboli, Taddeucci et al. (2012a, b) hypothesized that h could be the distance between the base of the slug and the camera; however, if most of the pyroclasts are released from the top of the slug, h could correspond to the distance between the top of the slug and the camera. Moreover, using the temporal evolution of particle exit velocity, Cigala et al. (2017) report that equation (1) can give errors for h up to 100% if the equation fitting the observed velocity decay shows a R^2 less than about 0.95.

In order to shed new light on conduit pyroclast dynamics and the role of the main controlling parameters, we performed analogue experiments using the *jet-burster*, a transparent shock-tube in which a rapid decompression of a pressurized tube allows the release of particles. Several initial configurations (i.e., gas volume and pressure, particle size and amount, initial sample height from the exit, vent geometry) have been tested. The transparent setup allowed us to record the entire path of these particles both inside and outside the shock-tube by high-speed cameras. These experiments revealed a pyroclast acceleration-deceleration phase that influences the ejection velocity at the exit, which depends on the initial conditions, i.e. gas pressure and volume, initial sample height from exit and grain size range. These results, compared to processes that occur during actual Strombolian explosions, can be used to draw inferences on the processes controlling the dynamics of pyroclasts during low-scale explosive eruptions. Moreover, to better understand the significance of h , we apply

equation (1) to compute h in each experiment and compare it to the initially fixed one (i.e., initial sample height from exit). We found that equation (1) underestimates or overestimates its calculation with respect to fixed value due to acceleration-deceleration phase, and the error is higher at lower initial energy and with a sample deeper from the exit.

3.2 METHODS

3.2.1 THE EXPERIMENTAL TOOL: THE JET-BURSTER

The jet-burster (Fig. 3.1) is a shock-tube apparatus designed, developed, and implemented at the High Pressure High Temperature (HPHT) Laboratory of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome to simulate explosive eruptions. It consists of two superimposed cylindrical plexiglas tubes (outer diameter of 50.09 mm and inner diameter of 39.81 mm). The lower one (hereafter PT, i.e. pressurized tube, 1 m long) is connected to a compressor and a pressure gauge, used to create a pressurized air pocket; in the upper tube (hereafter AT, i.e. tube at ambient conditions, 2.054 m long), a variable quantity of sample is introduced. The two sections of the apparatus are isolated by a controlled-release diaphragm system consisting of a plexiglass joint with inside a teflon ring, a constantan wire (copper-nickel alloy) and a sealant plastic disk (diaphragm). The diaphragm breakage at a preset time, by means of electrical connections and an electronic trigger, allows the release of the pressure introduced into the PT and, subsequently, the ejection of the particles outside the AT. Two high-speed cameras, an OPTRONIS CR600x2 (2000 frame per second), subsequently replaced with a NAC MEMRECAM HX-3 (from 10000 to 20000 frame per second), and a NAC MEMRECAM HX-6 (from 5000 to 20000 frame per second), record each experiment in two different sections of the AT (Fig. 3.1) separated by an unrecorded shadow zone.

Our analysis is based on 39 (out of 98) experiments (Table 3.1) carried out with the following average conditions: 28 °C, 49% humidity, and an atmospheric pressure of 101.325 kPa (Table 3.2). For each experiment, the initial configurations of the following parameters were changed (Table 3.1):

- (i) Sample properties (size range and amount): the sample introduced in the AT was composed by fragments of *Schaumlava*, a basaltic lava from the East Eifel volcanic field (Germany) with 15% porosity and a density of 2.5 g/cm³ (Douillet et al. 2014), produced by mechanical crushing. The sample was separated by wet

sieving in three different size fractions: fine (0.5–1 mm), medium (1–2 mm), and coarse (2–4 mm). Moreover, the sample was introduced in three different amounts: 15, 30 and 60 g, occupying a volume of about 0.179, 0.358, and 0.716 cm³, respectively, in the AT.

- (ii) Initial sample height: we placed the sample on a metallic grid (weight ~ 3.9 g, pore diameter < 0.5 mm) located at 0.054 ± 0.004 m from the diaphragm (about 2 m from the exit). In some experiments we cut roughly in half the AT, inserting a fixed grid diaphragm at cut height, thus having a higher sample location (0.95 m from the exit).

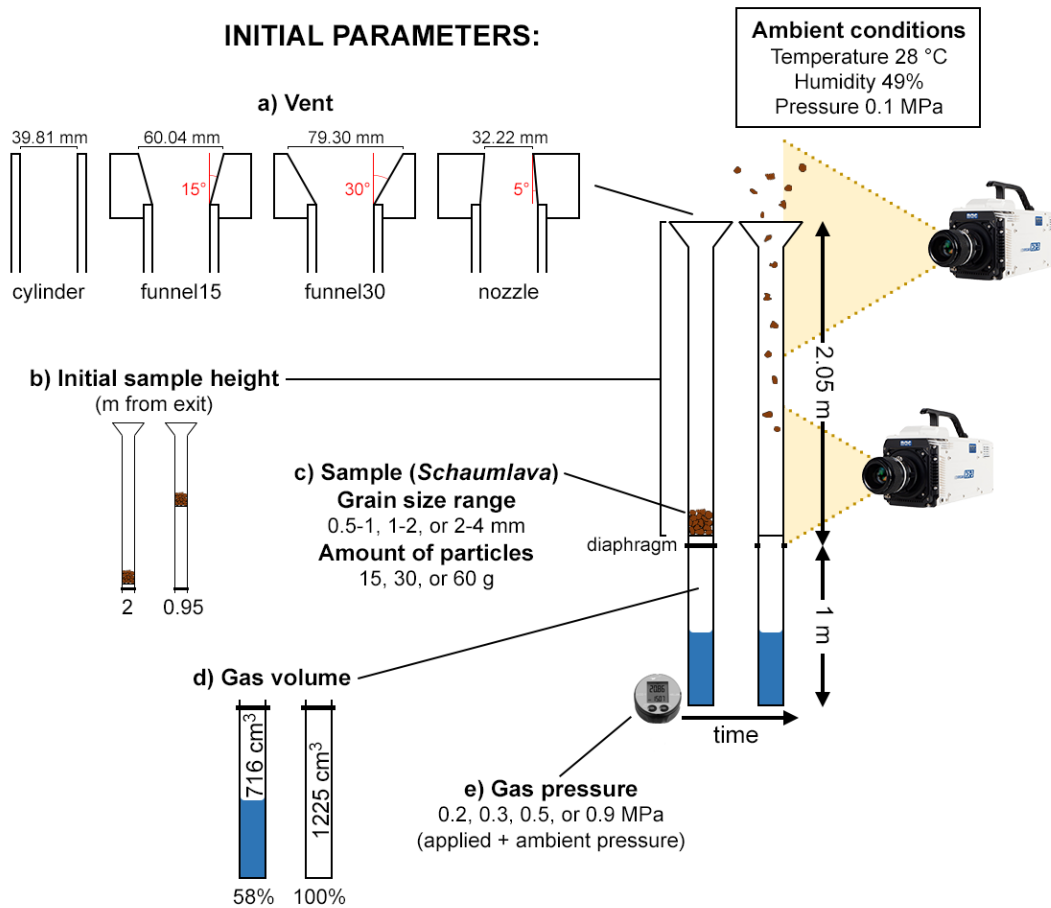


Fig. 3.1 Overview and setup of the jet-burster. To the right, two time-steps (pre- and post-breakage of the diaphragm) of the experimental device and the camera field of view (yellow dot-lined triangle) are shown (not to scale). The diaphragm isolates the AT (i.e. ambient tube, above it) from the PT (i.e. pressurized tube, below it). The inner diameter of the tubes is 0.039 mm. To the left, all input parameters are listed. **a** Four different vent geometries were used: cylinder (no convergence or divergence), funnel15 (divergence of 15°), funnel30 (divergence of 30°), and nozzle (convergence of 5°). **b** Two different initial sample heights were chosen, putting the sample on a metal grid located either just above the diaphragm (at 2 m from the exit) or roughly at half of the AT (at 0.95 m from the exit). **c** Three grain size ranges and three amounts of particles were chosen. **d** Two different air volume were considered: 716 and 1225 cm³, i.e. 58%, with water (blue area) filling the rest, and 100% of the PT, respectively. **e** Four gas pressures over the atmospheric pressure were applied to the PT.

Table 3.1 Summary of experiments performed and their initial configurations of parameters.

No. exp	Grain size range (mm)	Amount of particles (g)	Initial sample height (m)	Vent geometry	Volume ^a (m ³)	Pressure ^b (MPa)	Energy ^c (J)
23	1–2	32.26	2	Cylinder	7.16×10^{-4}	0.3	215.75
24	1–2	61	2	Cylinder	7.16×10^{-4}	0.3	215.75
25	1–2	15.8	2	Cylinder	7.16×10^{-4}	0.3	215.75
26	1–2	15.13	2	Cylinder	7.16×10^{-4}	0.2	144.15
28	1–2	31.5	2	Cylinder	7.16×10^{-4}	0.2	144.15
29	1–2	60.57	2	Cylinder	7.16×10^{-4}	0.2	144.15
31	2–4	15.66	2	Cylinder	7.16×10^{-4}	0.3	215.75
32	2–4	31.74	2	Cylinder	7.16×10^{-4}	0.3	215.75
33	2–4	63.36	2	Cylinder	7.16×10^{-4}	0.3	215.75
35	2–4	15.13	2	Cylinder	7.16×10^{-4}	0.2	144.15
36	2–4	31.74	2	Cylinder	7.16×10^{-4}	0.2	144.15
37	2–4	60.59	2	Cylinder	7.16×10^{-4}	0.2	144.15
44	0.5–1	15.33	2	Cylinder	1.23×10^{-3}	0.3	370.63
45	1–2	15.4	2	Cylinder	1.23×10^{-3}	0.3	370.63
46	2–4	15.22	2	Cylinder	1.23×10^{-3}	0.3	370.63
52	1–2	15.28	2	Funnel30	1.23×10^{-3}	0.3	370.63
53	2–4	15.14	2	Funnel30	1.23×10^{-3}	0.3	370.63
57	0.5–1	15.22	2	Funnel30	1.23×10^{-3}	0.3	370.63
58	0.5–1	15.22	2	Funnel30	7.16×10^{-4}	0.3	215.75
59	1–2	15.28	2	Funnel30	7.16×10^{-4}	0.3	215.75
60	2–4	15.25	2	Funnel30	7.16×10^{-4}	0.3	215.75
62	0.5–1	15.25	2	Nozzle	7.16×10^{-4}	0.3	215.75
63	1–2	15.25	2	Nozzle	7.16×10^{-4}	0.3	215.75
64	2–4	15.23	2	Nozzle	7.16×10^{-4}	0.3	215.75
67	0.5–1	15.17	2	Nozzle	1.23×10^{-3}	0.3	370.63
68	1–2	15.2	2	Nozzle	1.23×10^{-3}	0.3	370.63
69	2–4	15.22	2	Nozzle	1.23×10^{-3}	0.3	370.63
77	1–2	15.3	2	Funnel15	7.16×10^{-4}	0.5	358.95
80	1–2	15.35	2	Funnel15	1.23×10^{-3}	0.5	616.63
81	1–2	15.31	2	Nozzle	1.23×10^{-3}	0.5	616.63
82	1–2	15.29	2	Funnel30	1.23×10^{-3}	0.5	616.63
83	1–2	15.42	2	Cylinder	1.23×10^{-3}	0.5	616.63
84	1–2	15.25	0.95	Cylinder	1.23×10^{-3}	0.3	370.63
85	1–2	15.26	0.95	Cylinder	1.23×10^{-3}	0.5	616.63
86	1–2	15.2	0.95	Cylinder	1.23×10^{-3}	0.2	247.63
87	1–2	15.23	0.95	Funnel30	1.23×10^{-3}	0.3	370.63
88	1–2	15.32	0.95	Nozzle	1.23×10^{-3}	0.3	370.63
91	1–2	15.25	0.95	Cylinder	1.23×10^{-3}	0.9	1108.63
95	1–2	15.08	2	Cylinder	1.23×10^{-3}	0.2	247.63

^a The values of 7.16×10^{-4} and 1.23×10^{-3} m³ correspond to 58 and 100% of the PT, respectively.^b Total gas pressure, i.e. applied (0.1, 0.2, 0.4, or 0.8 MPa) + atmospheric pressure (0.1 MPa).^c Calculated by multiplying the total pressure by volume.

Table 3.2 Summary of the ambient conditions, tube diameter, air properties, and particle density considered here.

Ambient temperature ^a T_{amb} (K)	Humidity (%)	Ambient pressure P_{amb} (kPa)	Tube diameter L (m)
301.15	49	101.325	0.03981
Air density ^b ρ (kg/m ³)	Air viscosity μ (Pa s)	Particle density ρ_p (kg/m ³)	Heat capacity ratio
1.172	1.84×10^{-5}	2500	1.4

^a Corresponding to 28 °C.

^b Calculated from equation (3) by assuming specific gas constant of $287.058 \text{ J kg}^{-1} \text{ K}^{-1}$.

- (iii) Vent geometry: the release of particles occurred from different vent geometries, i.e. *cylinder* (no convergence or divergence), *funnel15* (divergence of 15°), *funnel30* (divergence of 30°), and *nozzle* (convergence of 5°), in order to investigate the influence of the different vent geometries on particle ejection.
- (iv) Gas properties (pressure and volume): we applied an air overpressure of 0.1, 0.2, 0.4 and 0.8 MPa (the latter only for sample at 0.95 from exit) over the atmospheric pressure (101.325 kPa); consequently, the total pressure in the PT was 0.2, 0.3, 0.5 and 0.9 MPa. Hereafter we refer to the pressure applied as the total pressure. Moreover, we considered two different air volumes occupying the PT: 7.16×10^{-4} (i.e. 58% of the PT, the rest of tube being filled by water) and $1.23 \times 10^{-3} \text{ m}^3$ (i.e. 100% of the PT), considering an employable space of 0.985 m in 1 m of PT. We used air to pressurize the jet-burster, since the difference in its heat capacity ratio γ (1.4) compared to the main volcanic gases in any terrestrial eruption, i.e. H_2O (1.33) and CO_2 (1.29), is of minor importance (Cigala et al. 2017).

3.2.2 VIDEO ANALYSIS

For each experiment, the data processing first provided a manual tracking of individual particles at the exit of AT using *ImageJ* (Abramoff et al. 2004) and its *MTrackJ* plug-in, in order to measure their velocity. Particle velocity was obtained by measuring the distance of each particle in 5 consecutive scaled frames and by averaging the velocity for this time interval. After tracking, we obtained the nonlinear velocity decay of the particles over time and computed the parameters h and v_{max} of equation (1) using the *MATLAB* software. Successively, we compared h derived from equation (1) to initial sample height from exit. For the experiments 23, 31, 45, and 53 we used the same method to track the particles also inside

the AT, at about 0.95 m from the exit; in this way, for the same experiment we obtained h and v_{max} of equation (1) below the exit to be compared with ones at the exit.

Furthermore, we focused on the experiments with the same grain size range, amount of particles and vent geometry conditions (i.e., experiments 25, 26, 45, 84, 85, 86, 91, and 95, for which we changed only the initial sample height and gas pressure and volume). For these cases, we manually tracked individual particles also inside the AT (i.e., from starting to exit) except for the shadow zone, obtaining the point-by-point velocity for the entire path. Generally, the spatial measurement error is given by the pixel size (0.001 m).

3.2.3 SCALING

In order to compare natural and experimental explosions, a fundamental step is to consider a non-dimensional analysis of the main controlling factors on the gas-particle flow. In this section we present the Reynolds and Stokes numbers, calculated both inside and outside the AT (Table 3.3).

Table 3.3 Summary of the non-dimensional numbers considered at the minimum (0.2 MPa) and the maximum (0.5 MPa) pressure for 1–2 mm sample located at 2 m from the exit and a cylindrical vent.

Pressure (Mpa)	Reynolds number ^a Re		Reynolds number of the particle ^d Re_p		Stokes number ^g St	
	Inside ^b	Exit ^c	Inside ^{be}	Exit ^{ef}	Inside ^b	Exit ^c
0.2	2.16×10^5	6.76×10^5	$4.35 \times 10^3 - 8.70 \times 10^3$	$1.62 \times 10^4 - 3.25 \times 10^4$	202.5 – 405.0	169.7 – 339.3
0.5	5.03×10^5	1.23×10^6	$5.72 \times 10^3 - 1.14 \times 10^4$	$2.14 \times 10^4 - 4.28 \times 10^4$	358.3 – 716.6	235.0 – 470.0

^a Calculated from equation (2) by assuming fluid density, dynamic viscosity, and diameter as Table 3.2.

^b Flow velocity derived using Python (Table 3.4).

^c Flow velocity derived from equation (8) (Table 3.4).

^d Calculated from equation (7) by assuming fluid density and diameter as Table 3.2.

^e Particle velocity derived by tracking inside the tube: 16.90 m/s and 108.55 for 0.2 and 0.5 Mpa, respectively.

^f Particle velocity derived by tracking at the exit: 11.46 m/s and 150.30 for 0.2 and 0.5 Mpa, respectively.

^g Calculated from equations (5) and (6) by assuming diameter, particle density, and dynamic viscosity as Table 3.2.

The Reynolds number (Re) is a dimensionless quantity used to predict flow patterns (laminar or turbulent) in different fluid flow situations and defined by the relationship between inertial and viscous forces:

$$Re = \frac{\rho UL}{\mu}, \quad (2)$$

where ρ and μ are the air density and viscosity, respectively, U is the flow velocity, and L is a characteristic linear dimension (in this case, the vent diameter; Clarke 2013; Cigala et al. 2017). Re is calculated using the one-dimensional isentropic theory (Saad 1985; Woods 1995), considering values shown in Tables 3.2 and 3.4 (flow velocity computation will be discussed below). In particular, the air density is estimated based on the ideal gas law:

$$\rho = \frac{P_{amb}}{R_{sp} T_{amb}}, \quad (3)$$

where P_{amb} is the ambient pressure, R_{sp} is the specific gas constant ($287.058 \text{ J kg}^{-1} \text{ K}^{-1}$), and T_{amb} is the ambient temperature. The air viscosity has been calculated based on the Sutherland's law:

$$\mu = \mu_{ref} \left(\frac{T_{amb}}{T_{ref}} \right)^{\frac{3}{2}} \frac{T_{ref} + S}{T_{amb} + S}. \quad (4)$$

Equation (4) provides the air viscosity for T_{amb} knowing the viscosity value (μ_{ref}) relative to a determined reference temperature (T_{ref}); S corresponds to the Sutherland constant at the reference temperature. For volcanic eruptions, Re ranges from 10^5 to 10^8 (Clarke 2013) or it can be as high as 10^{11} (Kieffer and Sturtevant 1984), while we estimated a range between 10^6 and 10^7 for eruptions at Stromboli (see Appendix B). For our experiments, Re is 10^5 inside the tube and ranges 10^5 – 10^6 at the exit (Table 3.1).

Table 3.4 Summary of initial (total applied in the pressurized tube) and final (reached at the exit) pressure, Mach number, and flow velocity (inside the tube and at exit) considered.

Initial pressure P (Mpa)	Final pressure ^a P_f (MPa)	Mach number ^b Ma	Flow velocity U (m/s)	
			Inside ^c	Exit ^d
0.2	0.15	0.77	85.29	266.72
0.3	0.20	1.05	135.40	364.03
0.5	0.32	1.40	198.50	486.30
0.9	0.60	1.82	271.20	633.05

^a Derived from equation (C.13).

^b Derived from equation (C.14).

^c Derived from Python.

^d Derived from equation (8).

The Stokes number (St) is a dimensionless number characterizing the behavior of particles suspended in a fluid flow. In particular, it describes the particle inertial response to the flow, and it is defined as:

$$St = \frac{\tau_p U}{L}, \quad (5)$$

where τ_p is the characteristic relaxation time of the particle (the time constant in the exponential decay of the particle velocity due to drag), calculated as follows (Elghobashi and Truesdell 1993; Carcano et al. 2013):

$$\tau_p = \frac{\rho_p d_p^2}{0.33 Re_p \mu}, \quad (6)$$

where ρ_p is the particle density, d_p is the particle diameter, and Re_p is the Reynolds number of the particle:

$$Re_p = \frac{d_p \rho |U - u_p|}{\mu}, \quad (7)$$

with a correction factor accounting for the relative velocities between gas flow (U) and particles (u_p). The particle velocity is calculated by the manual tracking of single particles inside (~ 0.12 – 0.62 m from top metallic grid) or outside (just above the exit) the AT. The St value was found to be 202.48–716.59 inside and 169.65–425.81 outside the AT (Table 3.3), hence gas and particles are not coupled. In theoretical studies, particles coarser than 0.5 mm are not coupled with the gas phase (Woods 1995; Carcano et al. 2013, 2014), as well as we estimated for Stromboli (see Appendix B).

Given the impossibility of direct, unambiguous measurements of the flow velocity of the pure gas (U), we calculated U by two methods, respectively for Re and St calculations is inside or outside the AT, and by neglecting the mass of the metal grid and the particles (Table 3.4). For the calculation inside the AT, the gas velocity (corresponding to the contact surface velocity; Section 3.3.1) is calculated using a script in Python, which is the implementation of Schleicher (1993) by Lewin Stein and Jörn Sesterhenn. For the Re and St calculation at the exit, U is defined as:

$$U = Ma \sqrt{\gamma R_{sp} T}, \quad (8)$$

where Ma is the Mach number, γ is the heat capacity ratio (dimensionless, for dry air is 1.4), and T is the absolute temperature (see Appendix C for derivation of Ma and T). Naturally, the gas flow velocity should be a bit lower than computed one due to the loss in kinetic energy used to accelerate the particles. Considering Ma , the experiments occurred in subsonic regime ($Ma < 1$) at 0.2 MPa, transonic regime ($Ma \sim 1$) at 0.3 MPa, and supersonic regime ($Ma > 1$) at 0.5 and 0.9 MPa (Table 3.4).

3.3 RESULTS

In this section, first of all we introduce the processes occurring in the jet-burster during a single experiment. Successively, we show the parameters h and v_{max} derived from equation (1) with respect to initial parameters. Finally, we show the particle velocities along the AT (values taken point-by-point) for selected experiments. Hereafter, we refer to h_V for h derived from velocity using equation (1) and h_R for the initial distance between the sample and the AT outlet in our experiments. In the experiments with a initial sample height of 2 m, but in which the particles have been tracked inside the AT at about 0.95 m from the exit (see section 3.2.2), we have to consider the difference (approximately 1.05 m) as h_R .

3.3.1 THE SHOCK-TUBE PROCESSES

Each experiment starts once the diaphragm breakage occurs at a preset time and, subsequently, gas-particles mixture accelerates toward the exit. It ends when the last particles either get out of the tube or lose their kinetic energy within the AT and start to fall back.

Figure 3.2 shows an example of 1-D profile of shock-tube processes occurring in the jet-burster for 0.2 MPa applied in the PT, produced by a numeric model simulation without particles. More generally, the system at the initial stage is as follows: (i) pressurized side in PT (conditions A) and (ii) ambient side in AT (conditions D), separated by the diaphragm. After the diaphragm breakage and the release of the pressure from PT, a compression wave and an expansion wave are generated. The compression wave is the first front and travels upwards (i.e., from the diaphragm into the ambient), while the expansion wave travels downwards inside the pressure region (Sod 1978; Zhang et al. 2015; Arciniega-Ceballos et al. 2015). High pressure in the PT and ambient pressure in the AT equilibrate to an intermediate pressure due to expansion and compression waves, respectively. Hence, over time the

configuration is: (i) pressurized side (A), (ii) expansion wave, (iii) conditions B, (iv) contact surface, (v) conditions C, (vi) compression wave, and (vii) ambient side (D). The contact surface is also a kind of wave moving upwards following the compression wave, in which there is no jump in the pressure, but in the density. It represents the boundary between the gas

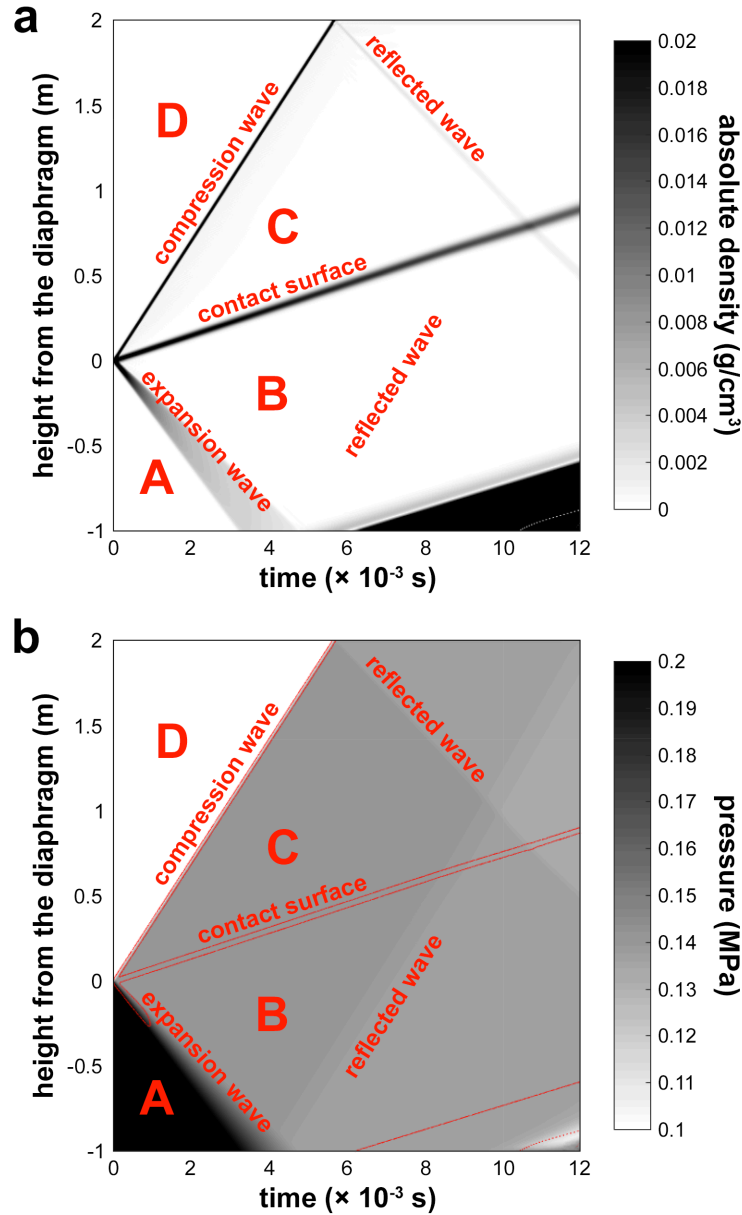


Fig. 3.2 Absolute density (a) and pressure (b) gradients of 1-D profile of shock-tube process occurring in the jet-burster (0.2 MPa applied in a volume of $1.23 \times 10^{-3} \text{ m}^3$, i.e. initial energy of 247.63 J), produced by a numeric model simulation without particles. The y-axes represent the height from the diaphragm located at 0 m , positive and negative values refer to the tubes at ambient and pressurized conditions, respectively. The compression and expansion waves (formed after the diaphragm breakage), their reflection, and the contact surface (boundary between regions initially separated by the diaphragm) are shown. Red lines in **b** correspond to the absolute density contour in **a**. Notably, the contact surface is visible only in **a** and reported in **b** for comparison. A: maximum pressure condition; B and C: intermediate pressure conditions; D: minimum (ambient) pressure condition. See the text for process explanation.

originally pressurized in PT and the ambient air in the AT, the regions initially separated by the diaphragm. This means that regions A and B contain gas from the pressurized side and regions C and D contain gas from the ambient side, but in regions B and C the conditions (temperature, pressure, etc.) are not the original ones because of the expansion and compression waves, respectively. The expansion and compression waves are reflected at the bottom and surface discontinuities, respectively, and come back, bouncing several times and decreasing progressively the pressure inside the jet-burster. Also the contact surface, as soon as the surface discontinuity is reached, is reflected downwards. Finally, at a certain time the pressure inside the jet-burster is homogenized. Interestingly, the pressure homogenizes immediately with the first two waves (i.e., compression and expansion ones), but the contact surface (i.e., the boundary of the gas jet) is actually the one which marks the motion of the gas. The gas moves at higher velocities at the center of the tube and at lower velocities at the tube walls.

In this configuration, the particles move upward with a velocity resulting from momentum transfer from gas to particles, and with an initial delay with respect to the contact surface. In fact, from the videos (Fig. 3.3) the contact surface is faster than particles in all the experiments, percolating among and overcoming them. For instance, Fig. 3.3 shows that the particles follow the contact surface with an initial delay of 0.29 ms near the diaphragm, which becomes 6.64 ms at the exit. This delay, which depends on the initial conditions, occasionally allows to observe the reflection of the compression wave propagating downward until it disappears due to the arrive of the particles that disturb the view. Following Fig. 3.2, above and below the contact surface the pressure is essentially the same, while this wave represents the volume of the accelerating gas. Since the pushing is from the bottom, at the start all particles move together as a plug. This plug-like phase typically occurs at the very beginning until the gas percolation is enough to pass through the layered sample. After that, the particles at the top move faster than the subsequent ones, with the tail particles showing the slowest velocity (Fig. 3.3). Along their path, the particles can collide both among them and with the wall of the AT, influencing their velocity and trajectory; these collisions occur particularly among the tail particles which, in some cases, fall back before reaching the exit. Occasionally, some particles move together as a cluster with a slightly faster velocity than the particles just around, causing secondary peaks on velocity decay graphs. At the exit, the compression wave develops a head vortex due to strong deceleration and air entrainment.

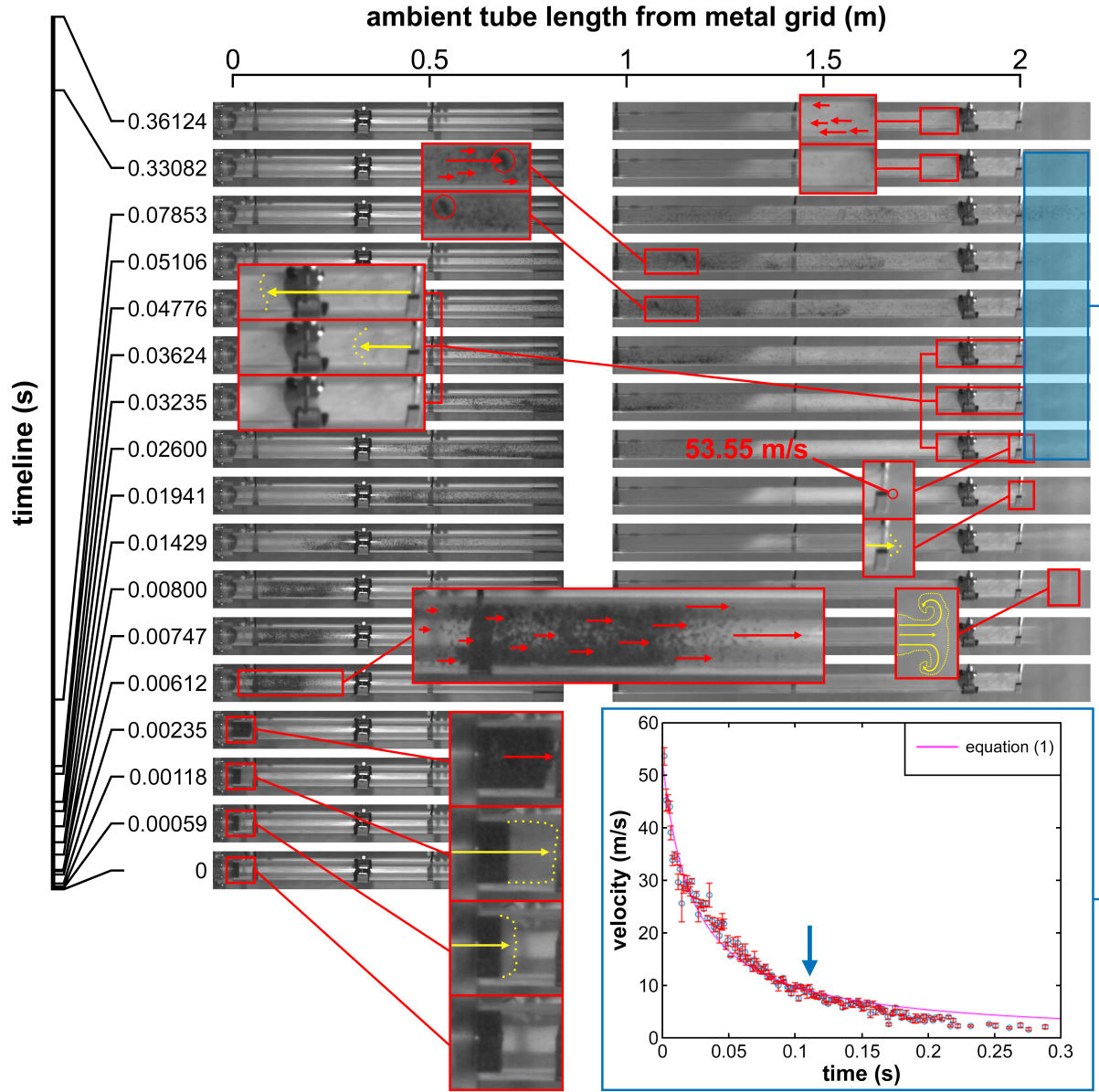


Fig. 3.3 Sequence of 0.36124 s image stills of experiment 45 taken at several times from the start of the experiment (time zero in the timeline) and rotated 90 degrees clockwise for convenience. Arrows refer to gas (yellow) and particle (red) movement vectors. From 0 to 0.00235 s, the faster compression wave (not visible) and contact surface (yellow dotted line) percolate among and overcome the particles, which start as a plug with an initial delay respect to the contact surface. Successively, at 0.00612 s the gas percolation disperses the particles, which move faster on the top. At about 0.008 s, the compression wave, the first reaching the exit and being reflected, develops a head vortex. At 0.01941 s, the contact surface (yellow dotted line) reaches the exit. At 0.026 s, the fastest particle (red circle, v_{max} is also indicated) reaches the exit sooner respect to the rest of particles. This delay allows to observe the contact surface reflecting downward (yellow dotted line, from 0.026 to 0.03624 s). Particle tracking at the exit area (blue area) produces the ejection velocity decay of particles over time (at the bottom on the right). Each point of the velocity decay represents the velocity of a single pyroclast, averaged over 5 frames, and time zero corresponds to the time at which the first particle is observed. Curve fitting is obtained from equation (1) by considering v_{max} 53.55 m/s. At 0.04776–0.05106 s, a cluster of particles (red circle) moves slightly faster than the particles around, causing a secondary peak on the velocity decay (blue arrow) when it reaches the exit. Between 0.33082 and 0.36124 s, particles start to fall back even without reaching the exit, dictating the end of the experiment.

3.3.2 INFLUENCE ON PARTICLE EJECTION

Depending on the initial conditions, the particles are ejected from the exit for a variable time (from 0.025 to 0.4 s), and therefore with specific patterns of velocity decay over time (Fig. 3.3). Maximum velocity at the exit (v_{max}), usually attained by the first particle, ranges from 11.46 ± 0.13 to 270.76 ± 2.55 m/s (for the experiments 36 and 91, respectively). The velocity over time decays from higher velocities as the input energy increases. Occasionally, we observe lower peaks in the velocity along the decay, due to some clustered particles moving slightly faster than the particles just around (Fig. 3.3). Ejecta velocity decays obtained from our experiments are well approximated by equation (1), since R^2 ranges 0.920–0.996.

Figure 3.4 shows that the main factor controlling v_{max} is obviously the energy (i.e., pressure multiplied by volume), with a linear relationship. An evident scatter is due to secondary factors such as h_R and grain size range. In fact, v_{max} is higher when the sample is

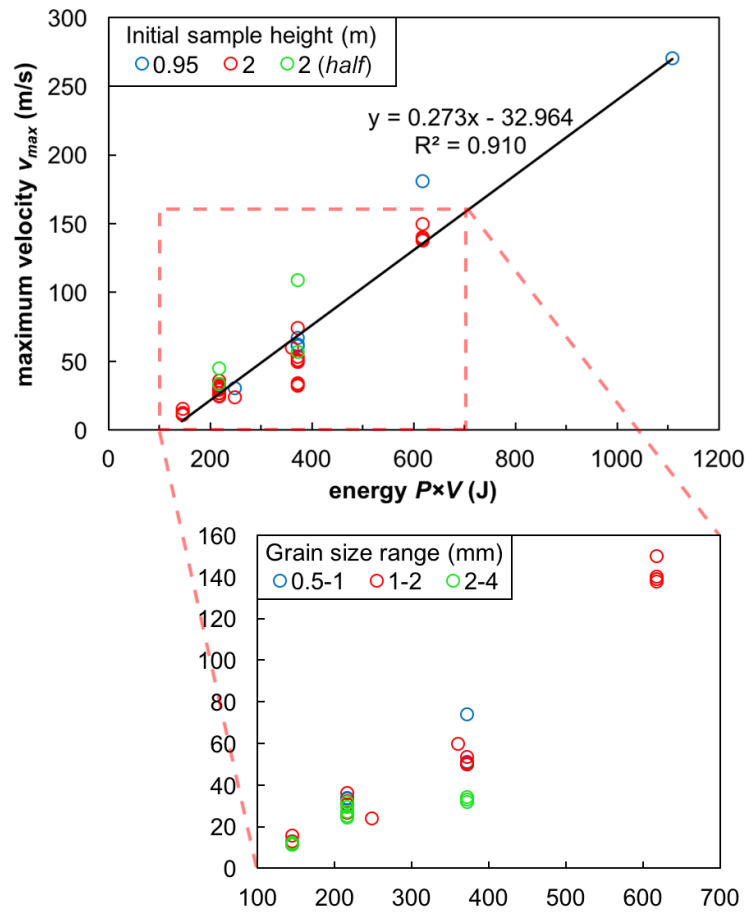


Fig. 3.4 On the top, maximum ejection velocity (v_{max}) measured below (*half*) and at the exit versus initial energy, considering all the experiments. On the bottom, only maximum velocity measured at the exit and with an initial sample height equal to 2 m (i.e. the red circles in graphic on the top) are plotted, distinguished by different grain size range. The standard deviation of uncertainty for v_{max} ranges from 0.126 to 16.206 m/s (mean of 2.196 m/s).

located at 0.95 m, rather than 2 m, from exit. Moreover, for a given experiment, v_{max} is higher when the particles are tracked at half AT rather than at the exit, implying an evident deceleration along particle path. Regarding the grain size range, when it decreases v_{max} is higher. Conversely, the amount of particles and vent geometry do not affect v_{max} .

The vent geometry influences particle ejection only at the exit. As an example, Fig. 3.5 shows three experiments at the same initial conditions except for the vent geometry. We note different dispersions of the particles: they follow the shape of the AT in the case of a cylinder vent, fan out with the funnel30 vent, and follow two directions that cross with the nozzle vent, while v_{max} is 31.96, 24.62, and 25.18 m/s, respectively. A slightly different v_{max} is always obtained among experiments with the same initial conditions but different vent geometries, although variations seems quite random, the higher value of v_{max} does not corresponding to any specific vent geometry.

Overall, there is no clear relationship between h_V and energy considering particle size range, amount of particles introduced in the tube, or vent geometry (Fig. 3.6). Conversely, the

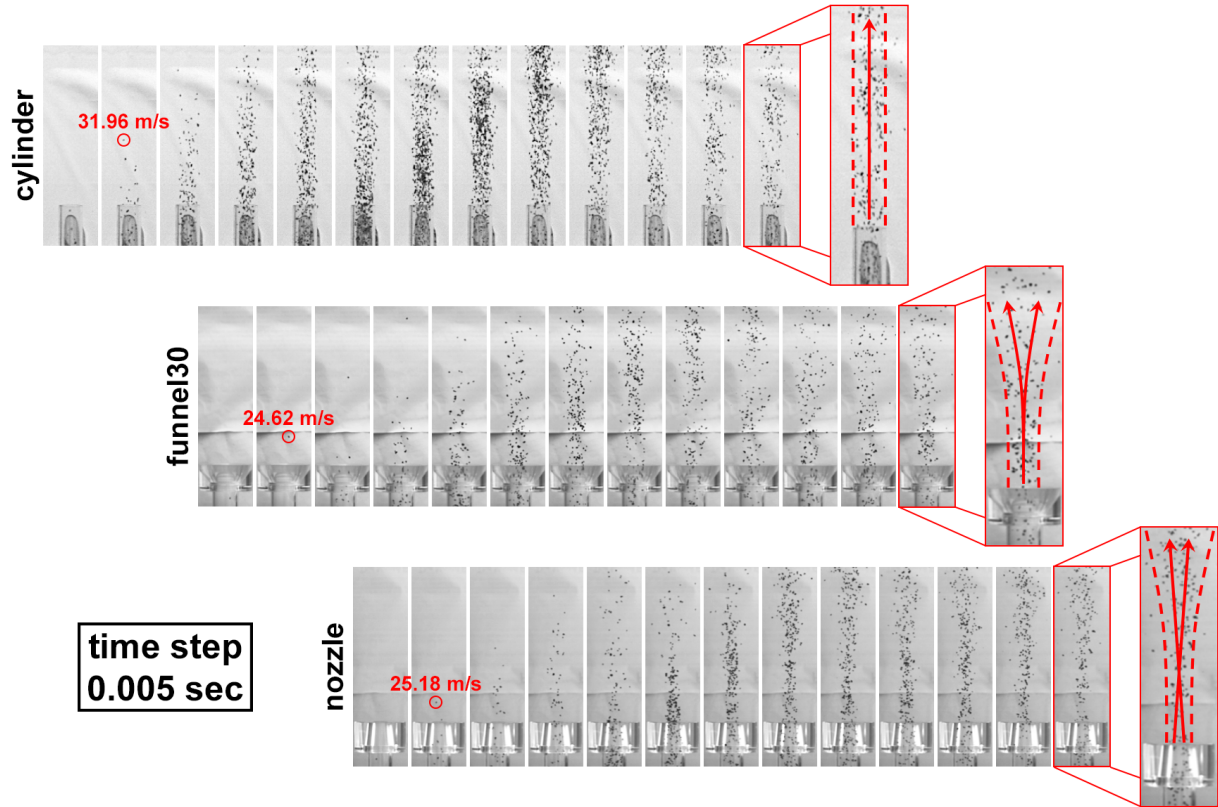


Fig. 3.5 Sequence of 0.06 s image stills taken each 0.005 s from three different experiments (i.e., experiments 31, 60, and 64), with the same initial conditions, except for the vent geometry (cylinder at the top, funnel30 at the center, and nozzle at the bottom). Grain size range: 2–4 mm, amount of particles: 15 g, gas volume: $7.16 \times 10^{-4} \text{ m}^3$, gas pressure: 0.3 MPa, initial sample height: 2 m. Dashed lines and arrows show the different dispersions of the particles at the exit for each vent geometry. Red circles denote the faster particle for each experiment, whose velocity at exit v_{max} is also indicated.

initial sample height evidences that when the sample is placed at 2 m from the exit h_V is always underestimated, and it approaches to the h_R as the $P \times V$ ratio increases (from 0.75–0.96 to 1.64–1.86 m at 144.15 and 616.63 J, respectively). Instead, by placing the sample at higher height (i.e., 0.95 m from the exit), h_V is always nearer to the h_R value at any $P \times V$, even if it is slightly underestimated (0.79–0.94 m) or, in one case, even overestimated (1.03 m). Interestingly, similar values among h_V and h_R are evident also considering the experiments in which the particles have been tracked below the exit, with a h_V range of 0.74–1.24 m.

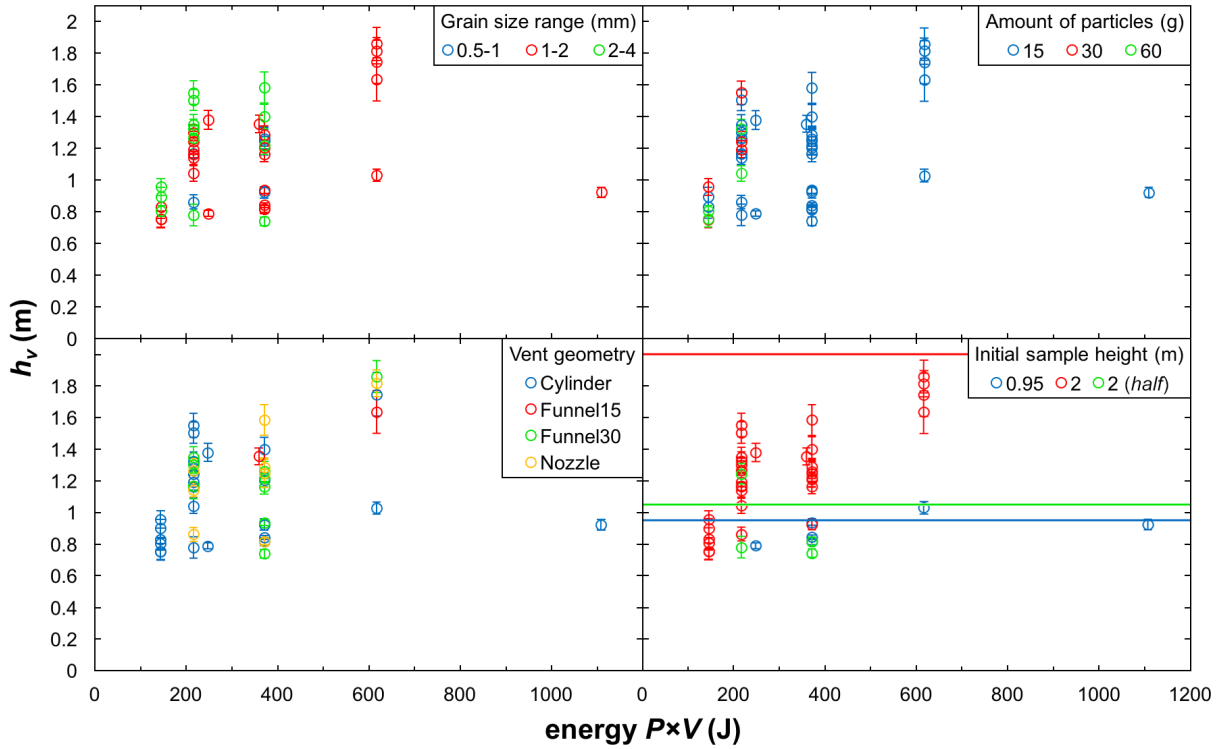


Fig. 3.6 The parameter h derived from velocity (h_V) versus energy, for each input parameter (i.e., grain size range, amount of particles, vent geometry, and initial sample height from the exit). The h_V zero corresponds to the point where sample is placed. The experiments in which the particles placed at 2 m from exit was tracked below it are also reported as *half*. Solid lines are indicative of the initial sample height (h_R), i.e. 0.95 (blue line), 1.05 (green line), and 2 (red line) m from the sample location. The 95% confidence intervals are also shown.

To better highlight the relation between h_V and energy in Fig. 3.6, we consider h_R/h_V as a measure of h_V effectiveness in retrieving the source depth of particles (i.e., when the ratio is close to 1, h_V is close to h_R) and we plot this ratio versus the energy (Fig. 3.7), evidencing an exponential regression.

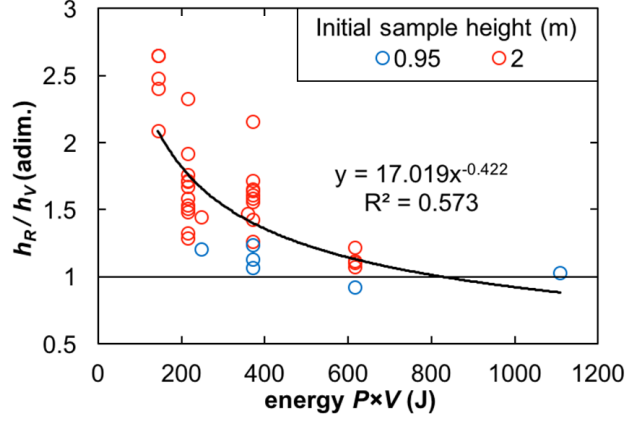


Fig. 3.7 Initial sample height (h_R) divided by h derived from velocity (h_V), i.e., a measure of h_V goodness, versus energy. Regression lines (thick lines) and h_R/h_V equal to 1 (thin line) are also shown. The measurement error for h_R is the pixel size (± 0.001 m), while the 95% confidence intervals for h_V are shown in Fig. 3.6.

3.3.3 PARTICLE ACCELERATION AND DECELERATION

Figures 3.8 and 3.9 show the relationships of height over time for some particles and their point-by-point velocity versus height and time along the ambient tube and at the exit at different initial energies. Depending on the initial energy, the rising of the particles recorded inside and outside the AT lasts from 0.03 to 0.5 s for higher and lower energy, respectively, with specific patterns of velocity. At first, each particle generally starts from the metal grid and suddenly accelerates according to the position at which it is initially located in the sample respect to the other ones (i.e., greater acceleration of the first, shallower particles with respect to deeper ones). Since particles start together in a sort of plug, it is very difficult to identify the specific point close to the metal grid from where each particle starts accelerating; therefore, we are not able to track the paths of individual particles until the gas percolation disperses them (Fig. 3.3). For this reason, particles do not start from velocity zero in Figs. 3.8 and 3.9.

Generally, after an initial acceleration, the first particle attains a peak of maximum velocity, after which, and before the exit, it starts decelerating. This peak is at a higher position and higher velocity, and consequently closer and closer to the exit, with increasing initial energy, until the first particle decelerates just once reached the exit with the highest energies (i.e., at 616.63 and 1108.63 J in Fig. 3.9). At the same initial energy, as soon as the end of the experiment approaches, the acceleration phase of the subsequent particles becomes shorter and shorter in height (i.e., the peak is deeper and deeper), followed by a more constant trend of velocity with height and time. At low initial energy, this trend is approximately a

constant deceleration, until the last particles stop rising (velocity equal to zero) before reaching the exit. The trend becomes more and more steep (and last particles stop closer to the exit) with increasing initial energy, until it becomes a constant acceleration at 1108.63 J. Notably, the several points of velocity peaks of each particle are aligned with each other.

The maximum velocity of the faster particle measured at the exit (i.e., v_{max}) almost never corresponds to the velocity peak reached along its complete path. Indeed, except for the case of a higher sample and a higher energy (616.63 and 1108.63 J in Fig. 3.9), v_{max} is always

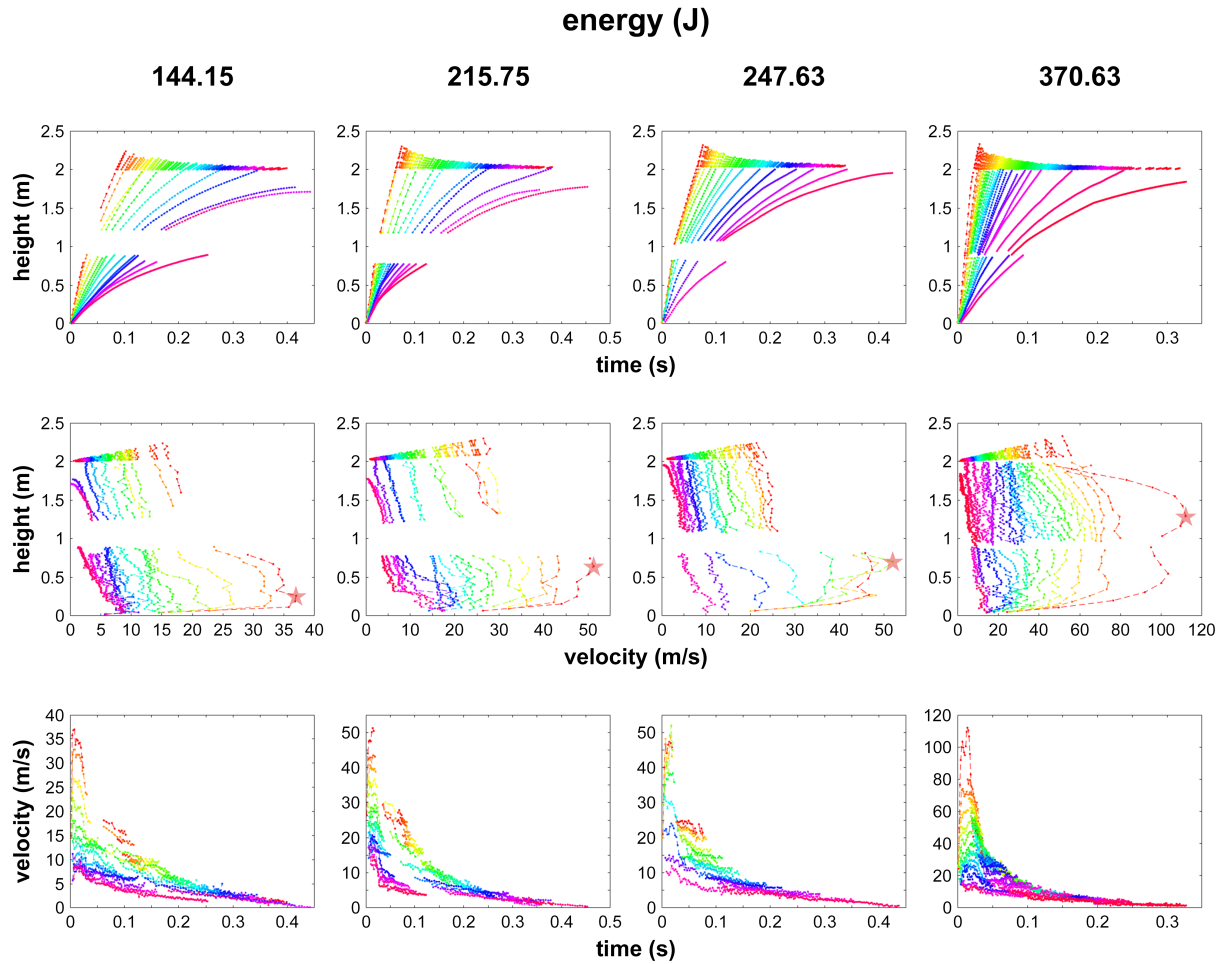


Fig. 3.8 Height over time and velocity versus height and time for some particles along the ambient tube and at the exit vent for each initial energy (i.e., 144.15, 215.75, 247.63, and 370.63 J for experiment 26, 25, 95, and 45, respectively) in the case of sample located at 2 m from the exit. Height 0 and 2 m are defined as the metal grid and the exit vent, respectively. Time zero corresponds to the time at which the first particle is observed to move. Each panel shows three tracked sections, i.e. the lower part of the ambient tube, the upper one, and the exit. An unrecorded shadow zone separates the lower and the upper part. Each point represents either the position or the velocity of a single particle taken over 10–20 frames. Colored dotted lines have been superimposed to the points of the same color to highlight each particle track. Red stars correspond to the maximum velocity peaks of each faster particle. Coordinates and lines color shades from red to violet, representing the first tracked particle and the last one, respectively, for each tracked section. The measurement error for height, not plotted in this chart, is the pixel size (± 0.001 m). Note variable x and y axes.

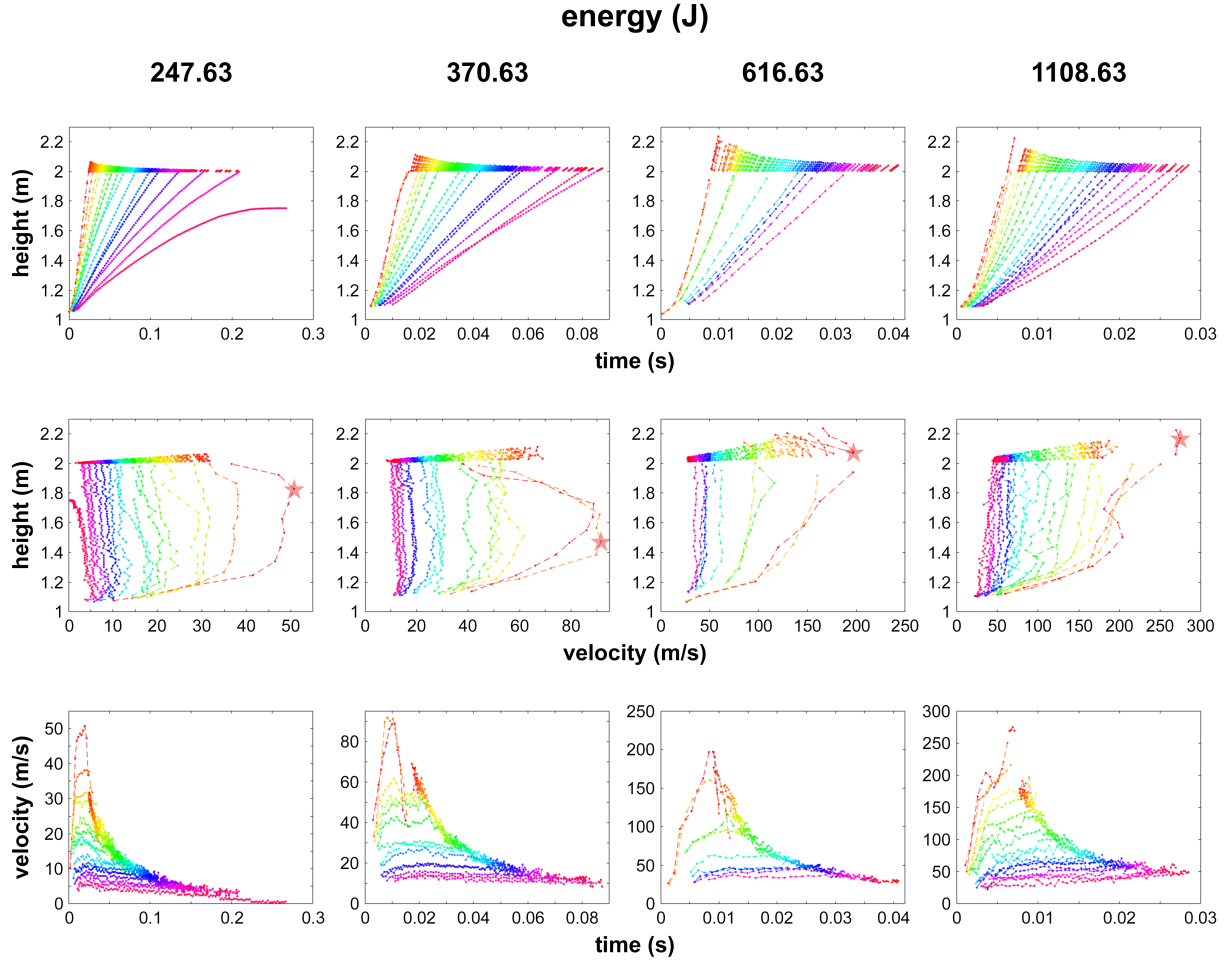


Fig. 3.9 Height over time and velocity versus height and time for some particles along the ambient tube and at the exit vent for each initial energy (i.e., 247.63, 370.63, 616.63, and 1108.63 J for experiment 86, 84, 85, and 91, respectively) in the case of sample located at 0.95 m from the exit. Height 1.05 and 2 m are defined as the metal grid and the exit vent, respectively. Time zero corresponds to the time at which the first particle is observed to move. Each panel shows two tracked sections, i.e. the upper part of the ambient tube and the exit. Each point represents either the position or the velocity of a single particle taken over 10–20 frames. Colored dotted lines have been superimposed to the points of the same color to highlight each particle track. Red stars correspond to the maximum velocity peaks of each faster particle. Coordinates and lines color shades from red to violet, representing the first tracked particle and the last one, respectively, for each tracked section. The measurement error for height, not plotted in this chart, is the pixel size (± 0.001 m). Note variable x and y axes.

lower than the velocity peak attained inside the AP. The exponential regression between v_{max} and the height at which the velocity peak is reached (Fig. 3.10a) suggests that higher v_{max} is recorded for higher height of velocity peak.

Considering the flow velocities inside the tube originated by a gas volume of $1.23 \times 10^{-3} \text{ m}^3$ (Table 3.4) and the velocity peaks of each first particle (Figs. 3.8 and 3.9), the first particle reaches from 59 to 101% of the flow velocity with an increase of energy (from 247.63 to 1108.63 J, respectively). At the same gas volume, in the cases of lower energies (i.e.,

247.63 and 370.63 J) particles successively decelerate inside the tube and lose at exit from 54 to 25% of their velocity peak.

To highlight the influence of the acceleration-deceleration phases on h_V , we plot h_R/h_V versus the height of the velocity peak (Fig. 3.10b). The logarithmic regression evidences that a higher, closer to the exit, velocity peak, and thus higher initial energy and higher acceleration phase, generates h_V values closer to h_R .

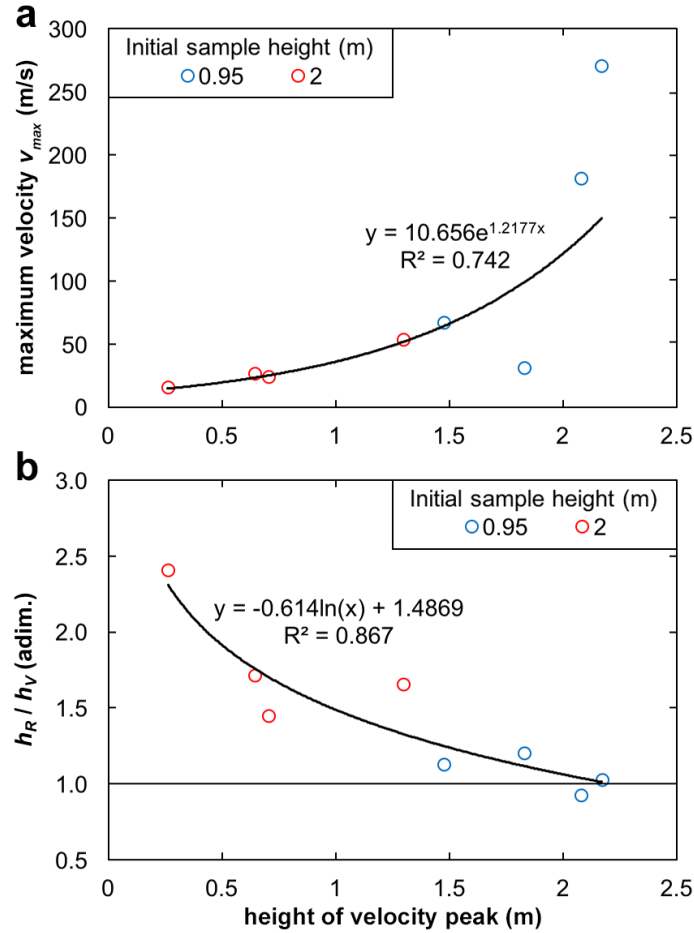


Fig. 3.10 Height of the velocity peak for the experiments shown in Figs. 3.8 and 3.9 versus maximum ejection velocity (v_{max}) measured at the exit (a) and initial sample height (h_R) divided by h derived from velocity (h_V), i.e., a measure of h_V goodness (b). Regression lines (thick lines) and h_R/h_V equal to 1 (thin line) are also shown. The standard deviation of uncertainty for v_{max} ranges from 0.126 to 16.206 m/s (mean of 2.196 m/s). The measurement error for h_R and height of peak velocity is the pixel size (± 0.001 m), while the 95% confidence intervals for h_V are shown in Fig. 3.6.

3.4 DISCUSSION

In this section, firstly, we summarize and interpret the dynamics observed in the transparent AT, from the start of the experiment to the output of the particles. These include

systematic changes in particle velocity with height and time, controlled by the input parameters, and processes that drive particle acceleration-deceleration phases. Then, we draw inferences on the parameter h_V and its significance.

3.4.1 GAS-PARTICLE DYNAMICS IN THE CONDUIT

The observed delay in the start of motion between the contact surface and the particles (Fig. 3.3) reflects the inertia of the particles in their coupling with the carrier gas. In fact, from estimated Stokes numbers (Table 3.3) it results that gas and particles are not coupled, since particles are coarser than 0.5 mm (Woods 1995; Carcano et al. 2013, 2014). As already mentioned, once an experiment starts, the particles at the top move upwards faster than the particles at the bottom. Since the sample is composed by permeable, loose, layers of particles, the gas (and therefore the energy) initially hits first the bottom particles and then escape through the sample pores. In the meantime, the bottom particles transfer their momentum to the top ones by particle-to-particle interactions, causing the delay between the contact surface and the first particles. The percolating gas may provide an additional drag to the particles on top while expanding, while the subsequent ones on bottom gradually have undergone only the initial acceleration and do not experience a further drag by the already-passed gas. In our experiments, particle acceleration starts from bottom towards top, in analogy with the bottom-up fragmentation model, driven by upward acceleration of bubbly magma (Cashman and Scheu 2015), as opposite to the top-down fragmentation model (i.e., due to a downward-propagating decompression event; Cashman and Scheu 2015), and similarly to that for the slug buster, in which fragmentation starts to occur in the start from the top (Cocomello 2013, Taddeucci et al. 2013c).

The transparent AT shows that the particles are decelerated after an initial acceleration phase (Figs. 3.8 and 3.9). The potential energy of the pressurized gas turns into kinetic energy via its expansion (Kieffer 1984; Woods and Bower 1995), causing the initial acceleration of the particles. However, it is not clear why deceleration occurs. Generally, particles may decelerate due to (i) energy dissipation caused by particle-particle and particle-wall interactions (Morgado and Oppenheim 1997; Sommerfeld and Huber 1999), (ii) gravity, or (iii) deceleration of the gas carrier, also considering the degree of gas-particles coupling (i.e., the Stokes number; Kieffer and Sturtevant 1984; Burgisser et al. 2005; Carcano et al. 2013). Slower particles and/or with more inclined directions are observed to hit frequently either among them or the inner surface of the 2-meters-long tube, slowing down their velocity further and getting out of trend with respect to the curve fitting of equation (1). However,

overall all particles are progressively dispersed by the gas flow during their rise, so that the particles that we tracked had only minimal, or no interaction with the other ones or with the wall of the tube. Gravity, decelerating particles downward at 9.8 m/s^2 , is entirely negligible in our case except for the slowest particle at the end of each run, considering that the slowest tracked particles decelerate from ~ 10 to $\sim 5 \text{ m/s}$ in 0.1 s , at a rate of about 50 m/s^2 (Fig. 3.8). Thus, the observed particle deceleration phases most likely represent the slowing of the carrier gas, mediated by the dynamics of two-way coupling between gas and particles. Gas deceleration in the AT occurs due to friction against the tube walls and through energy dissipation in internal turbulence and gas-particle interactions. Once the diaphragm breaks, particles are carried by the gas with an acceleration rate that is function of the Stokes number, hence of their degree of coupling with the gas: if they are fully coupled ($St \ll 1$) they would accelerate with the same velocity of the gas (Kieffer and Sturtevant 1984; Burgisser et al. 2005; Carcano et al. 2013). The Stokes numbers estimated here, the incremental delay between the contact surface and particles, in light of previous theoretical studies (Woods 1995; Carcano et al. 2013, 2014) confirm that gas and particles are poorly coupled in our case, and that particles move solely due to the initial push and consequent drag by the gas. Also, a phase of deceleration of the particles due to the reflection of the compression wave cannot be excluded, since the first particles get close to the exit after the reflection occurs (e.g., Fig. 3.3). Moreover, this reflection causes even a slight, almost imperceptible, deceleration of the contact surface (the latter changes its inclination with the passage of the reflection in Fig. 3.2). Hence, the reflection may have some effect only on those particles which have already detached from the sample mass, showing a deceleration. On the other hand, the final particles have undergone some acceleration, but then move upward by inertia when this reflection is passed yet, reaching their terminal velocity without decelerations like the previous ones.

In some experiments we observed some particles moving close to each other as a cluster and coming out faster than the surrounding ones are observable. It can be argued that such a particle cluster has a lower permeability with respect to the surrounding gas-particle mixture, thus the gas is not able to escape easily and it pushes more below the cluster, producing a velocity peak in the velocity decay trend.

Cigala et al. (2017) tested the same four vent geometry used here, finding a positive correlation between v_{max} and flaring vent walls, with peaks for funnel15. At the same initial conditions, here we found that the vent geometry influences only the dispersion of the ejected particles, while a similar v_{max} (with velocity peaks randomly related to a specific vent

geometry) is obtained. We argue that this contrasting evidence is due to different configurations of the two shock-tubes (initial pressure, gas used, distance of the sample from the vent, etc.) and to the fact that in Cigala et al. (2017) vent geometry shows an influence on v_{max} of subordinate importance compared to the influence exerted by the other conditions.

3.4.2 INFERENCES ON THE DERIVED DEPTH OF FRAGMENTATION LEVEL

As concerns understanding the effects of the controlling parameters on the observed gas-particle dynamics, one of the aims of this work is to understand what h_V represents. As mentioned above (section 3.1), it is derived from v_{max} using equation (1). Results reveal that the factors controlling v_{max} are, first of all, the initial energy (direct relationship), and, secondarily, h_R and grain size range (inverse relationship) (Fig. 3.4), while particle amount and vent geometry do not affect v_{max} . Cigala et al. (2017) found a negative correlation of v_{max} with tube length (i.e., h_R) and grain size range; instead, here we do not found a positive correlation with particle load and diverging vent walls, possibly due to very large differences in the overpressure versus tube length and mass load ratios in the different experimental setups. The acceleration-deceleration phase of the particles influences v_{max} recorded at the exit: the later the deceleration begins, and then the larger the acceleration, the greater the v_{max} (higher v_{max} is recorded for higher height of velocity peak; Fig. 3.10a). The acceleration-deceleration phase is a function of the initial energy and h_R (Figs. 3.8 and 3.9), as well as the grain size range (as it is v_{max} ; Fig. 3.4). The experiments in which the particle was tracked both below and at the exit support the influence of h_R on v_{max} : a given experiment yields an underestimated h_V if v_{max} is recorded at the exit (i.e., after a deceleration phase in the conduit) whereas a more realistic h_V (more similar to h_R) is obtained if v_{max} is measured deeper (i.e., at half of the AT, before the deceleration phase in the conduit).

A fundamental assumption in equation (1) is that particle velocity is constant within the conduit (Alatorre-Ibargüengoitia et al. 2010, 2011; Taddeucci et al. 2012b), or, at least, that particles have a short acceleration phase (Gaudin et al. 2014). Using the temporal evolution of particle exit velocity, Cigala et al. (2017) report that equation (1) can give relative errors for h_V up to 100% if the equation fitting the observed velocity decay shows a R^2 less than about 0.95. Moreover, a low R^2 may imply variations of particle velocity in the conduit. We argue that the significant acceleration-deceleration phases of particles evidenced here implies that the constant velocity assumption does not hold true in our case, making the application of equation (1) unsuitable if these phases are not taken into account. Indeed, the logarithmic regression shown in Fig. 3.10b suggests that equation (1) computes a more

suitable h_V value (i.e., h_R/h_V tends to 1) when explosions have a higher height of velocity peak, and thus higher initial energy and/or shallower sample position (Fig. 3.6), thus developing a deceleration phase closer, or beyond, the exit. Indeed, considering a deeper sample position, at lower initial energy h_V is always underestimated because faster particles decelerate more before reaching the exit (Fig. 3.11a). At the same sample position, higher initial energy can overestimate h_V if a deceleration phase in the conduit lacks due to a prolonged acceleration phase, so that deceleration would occur well above the exit (Fig. 3.11a). With a shallower sample position, the estimate of h_V is better due to a deceleration phase which occurs more and more beyond the vent rim as the initial energy increases (Fig. 3.11b). We note that in our experiments depth overestimates (i.e., $h_R/h_V < 1$) due to particle acceleration are rare, while in most cases it is the effect of deceleration which dominates, resulting in $h_R/h_V > 1$. Although unquantified, this observation suggests that, in natural cases, in-conduit pyroclast deceleration may have the strongest effect on the depth retrieval based on h_V .

3.5 CONCLUSIONS

Here, we performed scaled analogue experiments using a transparent shock-tube (i.e., the jet-burster), in order to better define the role of the source parameters on pyroclast ejection and investigate the unobservable-in-nature process of pyroclast acceleration and deceleration in the conduit. Testing several initial configurations (i.e., gas volume and pressure, particle size and amount, initial sample height from the exit, and vent geometry), data analysis led to the following results. First, the particle maximum velocity recorded at the exit increases with higher input energy, shallower sample, and lower grain size range. Second, different vent geometries produce variable ejection modes of particles at the exit, although with only slight and fluctuating changes of maximum velocity. Finally, a particle acceleration-deceleration phase in the shock-tube is observed, as a function of the initial conditions, which influences the particle maximum velocity recorded at the exit.

In our experiments we tested equation (1), an empirical model proposed by Alatorre-Ibargüengoitia et al. (2010, 2011) and applied to volcanic eruptions (Taddeucci et al. 2012b) to compute h , i.e. the depth from which pyroclasts are released. One of the major assumptions of this equation is a constant particle velocity in the conduit (Alatorre-Ibargüengoitia et al. 2010; Taddeucci et al. 2012), while here we provide evidence that particles move almost never at constant velocity, making the application of equation (1) to natural cases doubtful in

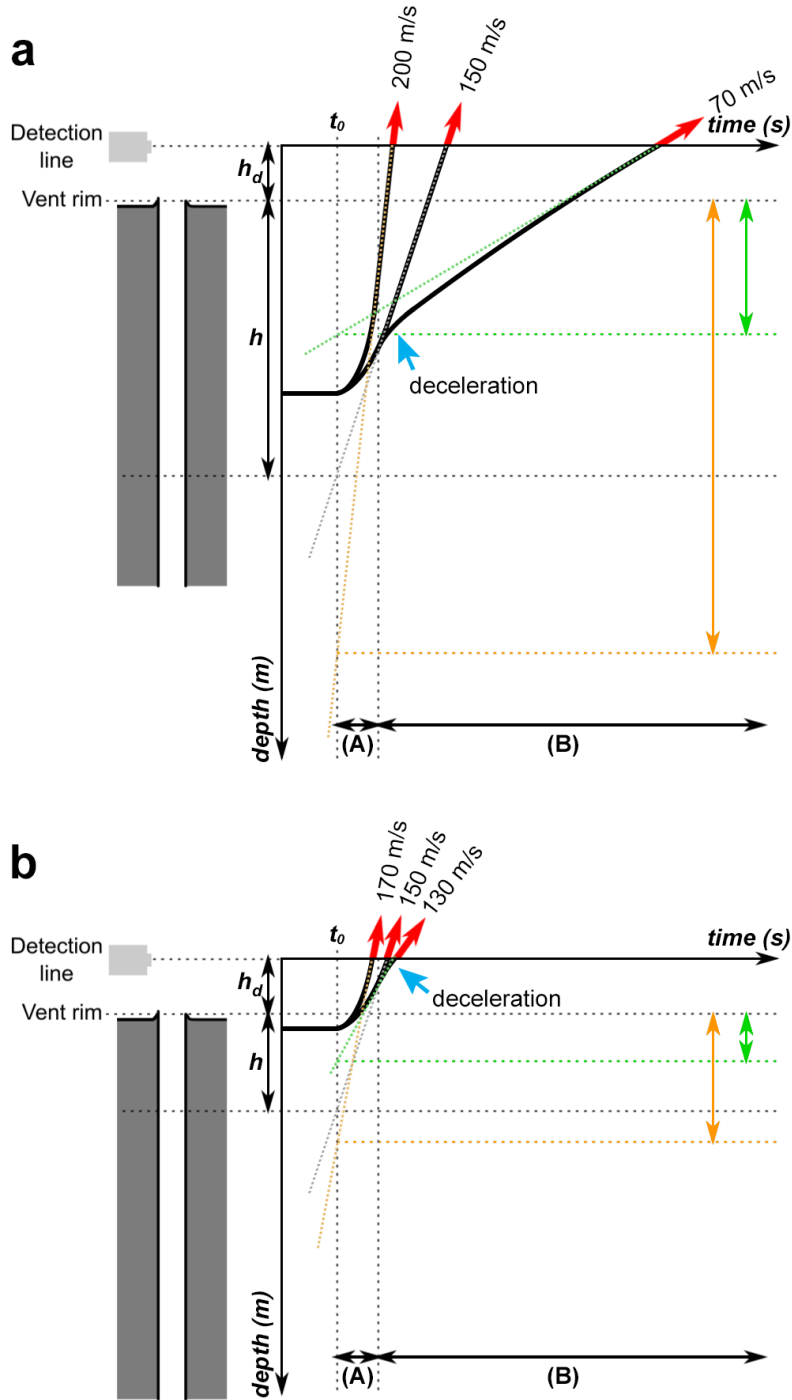


Fig. 3.11 Theoretical evolution of the ejection of the faster bomb during a single pulse. **a** By assuming an ideal situation of constant velocity (zero drag and gravity), the camera located at height h_d above the vent would measure a pyroclast velocity of 150 m/s. At time t_0 (i.e., the time of the slug burst) the bomb trajectory converges toward a characteristic depth (h), which represents the deepest possible source for bombs (dotted gray line). By assuming a larger acceleration phase (due to higher initial energy) the camera measures a higher pyroclast velocity (200 m/s), and the bomb trajectory converges deeper at time t_0 (dotted orange line), thus overestimating h (orange arrow). On the other hand, by assuming a deceleration after the acceleration phase (due to lower initial energy) the pyroclast velocity is lower (70 m/s), and the bomb trajectory converges shallower at time t_0 (dotted green line), thus underestimating h (green arrow). **b** If the faster pyroclast starts from a shallower position, the acceleration and deceleration phases are more reduced and the camera measures a pyroclast velocity more similar to the real one, with minor h overestimate (orange arrow) and underestimate (green arrow). (A) and (B) denote the acceleration and the travel-deceleration phases, respectively. Modified from Gaudin et al. (2014).

the presence of significant acceleration-deceleration phases. We found that equation (1) returns an error of estimation of h in function of the initial energy and the distance sample-vent (i.e., higher error for lower initial energies and a sample deeper respect to exit), which define a specific acceleration-deceleration phase. Indeed, at low initial energy or when the sample is deeper from exit, h derived from equation (1) (i.e., from the maximum ejection velocity at the exit) is always underestimated respect to the real one (i.e., h_V). In this case, a lower measured maximum ejection velocity is obtained due to the higher particle deceleration before reaching the exit. The parameter h derived approaches the real one at higher initial energy and a shallower sample (developing a particle deceleration phase closer, or beyond, the exit), as well as with finer grain size range, even if slightly underestimated or overestimated. Translated into source depth measurements at erupting volcanoes, we would anticipate more realistic depth estimates to be obtained in shallower and more energetic explosions, with an increase in depth underestimation as explosions get deeper and/or weaker.

A complication in a real eruption in comparison with an experiment is that pyroclasts do not come exactly from the same depth in a single pulse but, conversely, in more pulses from different depths (Taddeucci et al. 2012b; Gaudin et al. 2014; Bombrun et al. 2015; Del Bello et al. 2015; Capponi et al. 2016). The jet-burster, even if representative of a simpler process, shows great potential for the investigation of ejection and conduit dynamics in nature. Indeed, it can help quantify in-conduit trends of pyroclast acceleration-deceleration, in order to take them into account to compute the fragmentation depth by revised equation (1), even adding the Stokes number to the equation. Further experiments should be performed to investigate the role of other source parameters on pyroclast ejection. For instance, experiments could be performed either using larger gas volume and higher pressure or modifying the diameter and length of the tube (to investigate the influence of conduit size) and particle size distribution (e.g., using very fine particles to simulate volcanic plumes).

3.6 ACKNOWLEDGEMENTS

This work was supported by the Italian “Laboratorio Alte Pressioni Alte Temperature di Geofisica e Vulcanologia Sperimentali (HPHT)” at Istituto Nazionale di Geofisica e Vulcanologia (INGV) in Rome. We acknowledge Jörn Sesterhenn and Lewin Stein for the code in Python utilized here.

CHAPTER 4 – CONCLUDING REMARKS

The aim of my work was the definition of the relationships between the physical parameters inside the volcanic conduit and their influence on the modes of pyroclast ejection during Strombolian explosive eruptions. I achieved this aim using two approaches.

Regarding the first kind of methodology, which I report in chapter 2, the investigation of the exclusive dataset recorded by a surveillance camera and composed of more than 4000 events from five 72-h-long time-windows of observation during the 2005–2009 period provides a detailed database of normal eruptive activity at Stromboli. In attempt to characterize this eruptive style, changes in activity and vent locations at different time-scales, i.e., from hours-to-days to months-to-years, are highlighted. The grouping of these changes, even if applicable only to normal explosive activity, evidences (i) systematic changes in the activity style (e.g., jet parameters, explosion intensity and frequency) over the shortest time scale, and (ii) the evolution of individual vents (e.g., migration and merging) and vent areas, and subsidence of the whole crater terrace followed by re-establishment of vent zones over the longest time scale. Results from this methodology provide information on the conduit system at Stromboli, held in activity and vent evolution. Firstly, a dual behavior of the conduit system, with the NE vent area operating independently of the joint SW+C areas, is deduced by several lines of evidence, although deeper system changes can affect all three vent areas. Secondly, a hierarchy of depths in the conduit system that controls the explosive activity at Stromboli is inferred. At the shallowest depth (<150 m below the crater terrace), slug size and conduit-vent geometry control local explosion parameters, while simultaneous versus alternating activity at twin vents is perhaps due to a shallow branching of the conduit. At a deeper level (probably at 220–275 m of depth), both the conduit system geometry and level of free surface determine which specific vent will host the explosions and also some more general explosion features within a vent area. The aforementioned link between the C and SW vent areas may be placed just above this depth. At the deepest level (i.e., corresponding to the magma reservoirs at 3–3.5 km or at 7–9 km of depth), the features of the conduit system are common to all vent areas, roughly balancing the overall increases and decreases in activity across the NE and SW+C areas.

These new data allow a better understanding of this eruptive style at Stromboli. Therefore, the analysis of activity behavior and vent evolution may provide basic inferences

on the geometry and dynamics of conduit systems also for other persistent multi-vent systems worldwide, such as Masaya, Pu'u 'O'o, Etna, Fuego, and Yasur. Furthermore, results are also relevant in order to mitigate the associated hazards. For instance, the observed changes over time in the explosion parameters (i.e., jet orientation, height, and width) and in the distribution of their source vent can be used to define areas prone to ballistic dispersal and variations in their location.

The second methodology, which I explain in chapter 3, was applied to perform several sets of scaled analogue experiments on starting gas-particle jets using the jet-burster. This transparent shock-tube allowed to focus on the effects of the initial source conditions (i.e., gas pressure and volume, sample position, size and amount of particles, vent geometry) on the dynamics of the gas-particle mixture in the conduit and its ejection from the vent. Testing several initial configurations, the experimental data presented here indicate that the particle maximum velocity recorded at the exit is a function of the input energy (direct relation), sample depth from the vent (inverse relation), and grain size range (inverse relation). The experiments showed a trend of particle acceleration-deceleration in the shock-tube that variably depends on some initial conditions (i.e., initial energy, sample position, and particle size) and influences the particle maximum velocity recorded at the exit. In contrast, vent geometry does not show a significant effect on the maximum velocity, influencing only the mode of particle ejection at the exit. These results shed innovative inferences on the processes controlling the dynamics of pyroclasts at the volcanic scale. Furthermore, I tested the applicability of the model proposed by Alatorre-Ibargüengoitia et al. (2010, 2011) on the experiments performed here. Results reveal that the model returns a higher error of estimation of h for a lower initial energy and a deeper sample position respect to the exit. This error is due to the invalid assumption that particle velocity (from which h is derived) is constant in the conduit (Alatorre-Ibargüengoitia et al. 2010; Taddeucci et al. 2012b). On the contrary, these experiments evidence that particles move almost never at constant velocity. Indeed, in cases of lower initial energy and deeper sample, a lower maximum ejection velocity is recorded by the camera due to the higher particle deceleration before reaching the exit. Concerning model application to real eruptions (Taddeucci et al. 2012b), I suggest a revision of the model that takes into account the acceleration-deceleration trends evidenced in the present study. Further investigation will help quantifying these trends, to be used as input parameters in an advanced empirical model based on observable parameters during a real eruption (e.g., particle velocity, coupling with gas, grain size range, etc.), in order to obtain the ascent modes of pyroclasts in a real volcanic conduit.

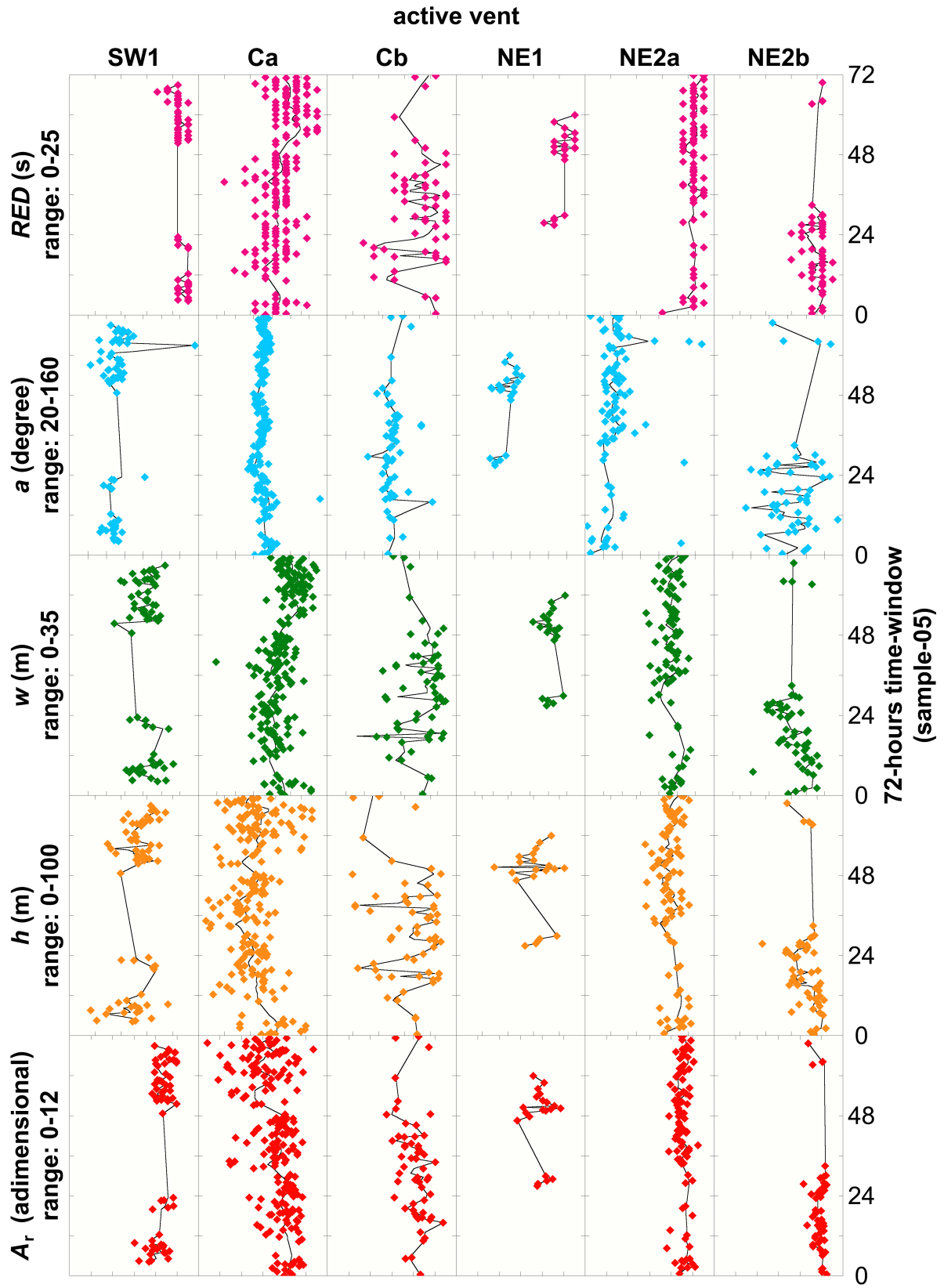
At the chosen observational conditions, some influences of the invisible gas on particle dynamic (e.g., which wave sets the particles in motion and other effects of the particle-gas coupling) are unclear here and need to be investigated more. Further experiments considering just one layer of particles, not confined by overlying ones, and using a gas-tracker probably will help to answer these pending questions. Also, the coupling of these experiments and microseismic signals, as already introduced in Cigala et al. (2018), can help to know the gas-particle mixture dynamics. Another approach could be to use a Laser Doppler Velocimetry, in order to better define the degree of gas-particle coupling and its effect on jet dynamics. Further experiments should be performed to understand the role of other source parameters on pyroclast ejection. For instance, the role of the conduit diameter on the height at which the particles start decelerating is also to be investigated: in this regard, it is important to know if with a larger diameter the gas would have space to expand more toward the sides than upwards, causing a deeper particle deceleration. Other experiments could be performed either using higher input energy or changing particle size (e.g., using very fine particles to mimic and study the volcanic plumes). Therefore, the work I have discussed in chapter 3 could be considered as preliminary, as the impact of particle ascent on the observed dynamics at vent still needs to be described at later stages. However, the results of the experiments I performed, although preliminary, provide insights on the dynamics of non-coupled gas-particle mixtures, relevant for the natural cases.

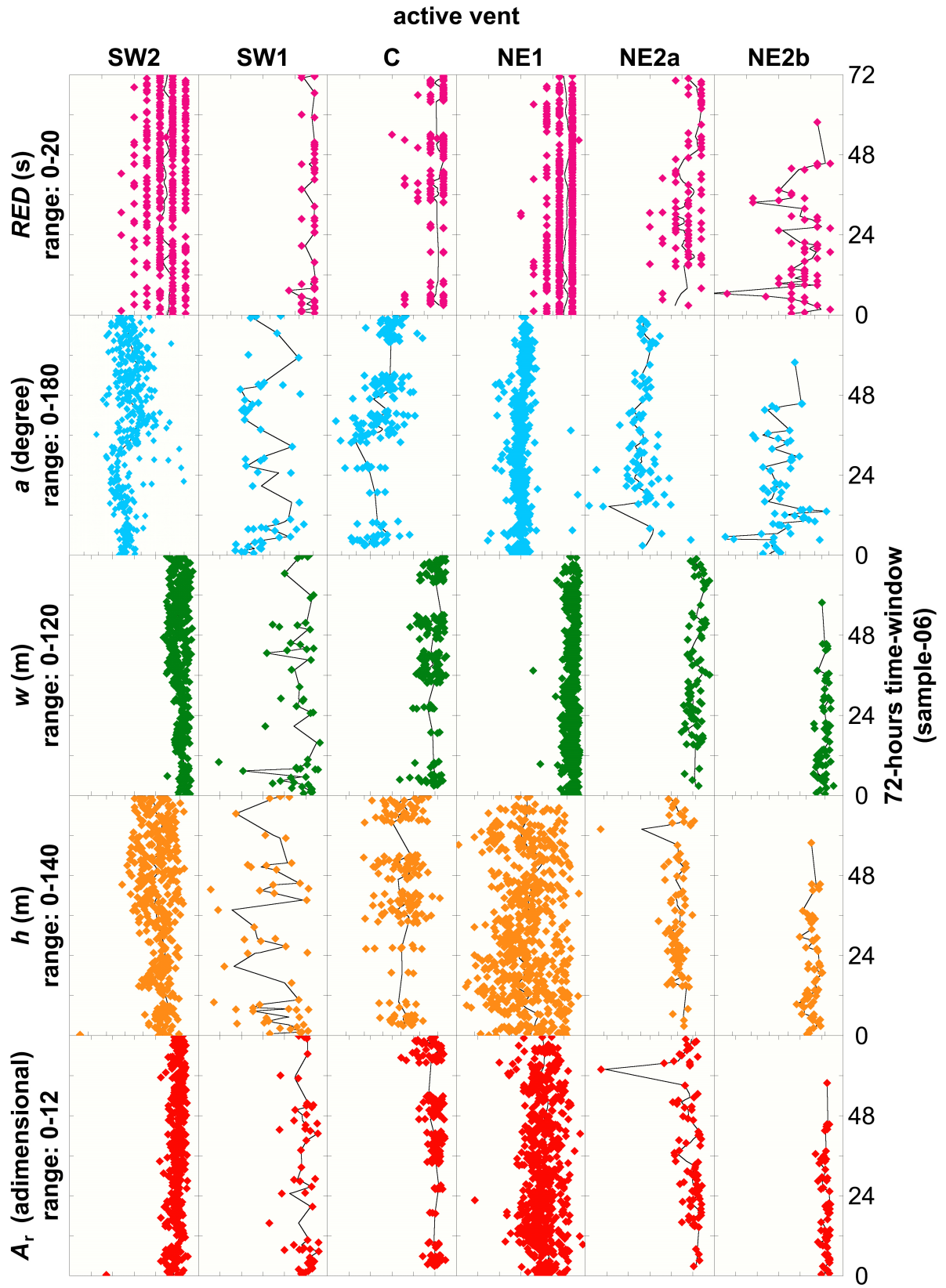
Finally, as a general conclusion, my thesis provides a promising link between the field observations and laboratory analogue experiments, in order to better define quantitatively the relationships between volcanic conduit dynamics and pyroclast ejection. From chapter 3 it is clear that the jet-burster, even if representative of a simpler process, shows great potential for a quantitative investigation of pyroclast ejection and conduit dynamics during mild explosive eruptions in nature. In fact, through the experiments, the parameters of chapter 2 (such as height, width, and ejection angle) can be reproduced and studied in the laboratory, relating them to the hidden factors that play a role in shaping explosive activity (such as depth at which particles start, conduit geometry, and vent shape). For instance, the delay in time between the arrival of the shock wave to the vent (measurable with microphones or with the formation of a vortex ring) and/or of the contact surface and the arrival of the pyroclasts could be used to make deductions on the depth of the explosions. Moreover, the vent geometry applied on the jet burster does not change much the ejection angle of the particles, suggesting that the different ejection angle measured at Stromboli (chapter 2) is mainly due to variations in depth and not in the geometry of the vent. Even if real eruptions are much more complex

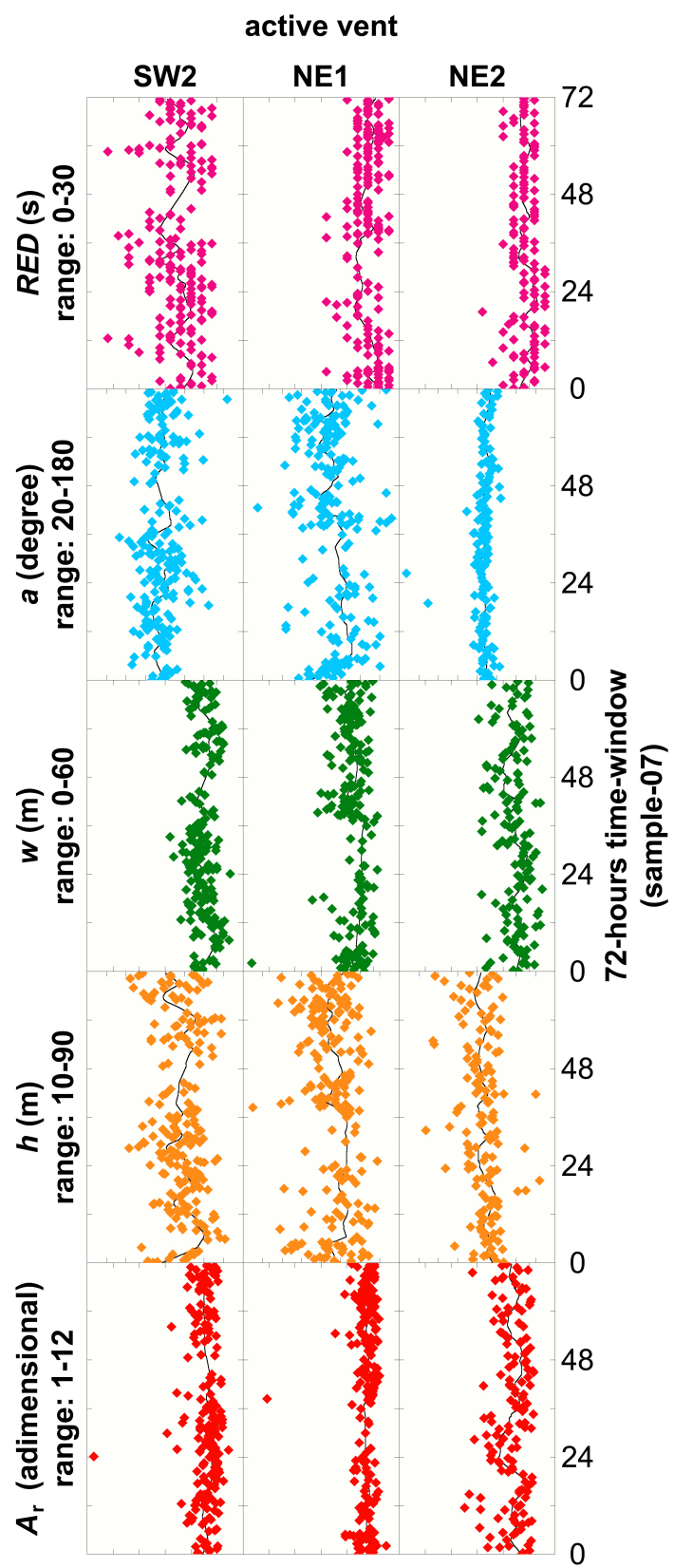
than experiments, the latter help to understand a relatively simple process, to which gradually it is possible to add complexity and mimic the real eruptions. For instance, pyroclast ejection with multiple pulses and sub-pulses, as occurs in natural cases (Taddeucci et al. 2012b; Gaudin et al. 2014; Bombrun et al. 2015; Del Bello et al. 2015; Capponi et al. 2016), could be replicated by partitioning the pressurized tube in several sections. Furthermore, the conduit branching of the twin vents (see chapter 2) may be replicated by connecting 2 pipes to the upper one via a joint, in order to study the ascent of a slug and the resultant dynamics. Moreover, particle-particle and particle-wall collisions in the tube could be traced, with inferences on the final particle velocity and trajectory. Moreover, I believe that the jet-burster could become a strong asset relevant not only in volcanic scenarios. Just slight changes of its setting can lead to its application to numerous engineering applications, as well as to different geological system in which a gas reservoir is below a conduit, such as geysers, mud volcanoes, and other eruptive styles (e.g., Vulcanian and hydrothermal ones) on Earth and other planets.

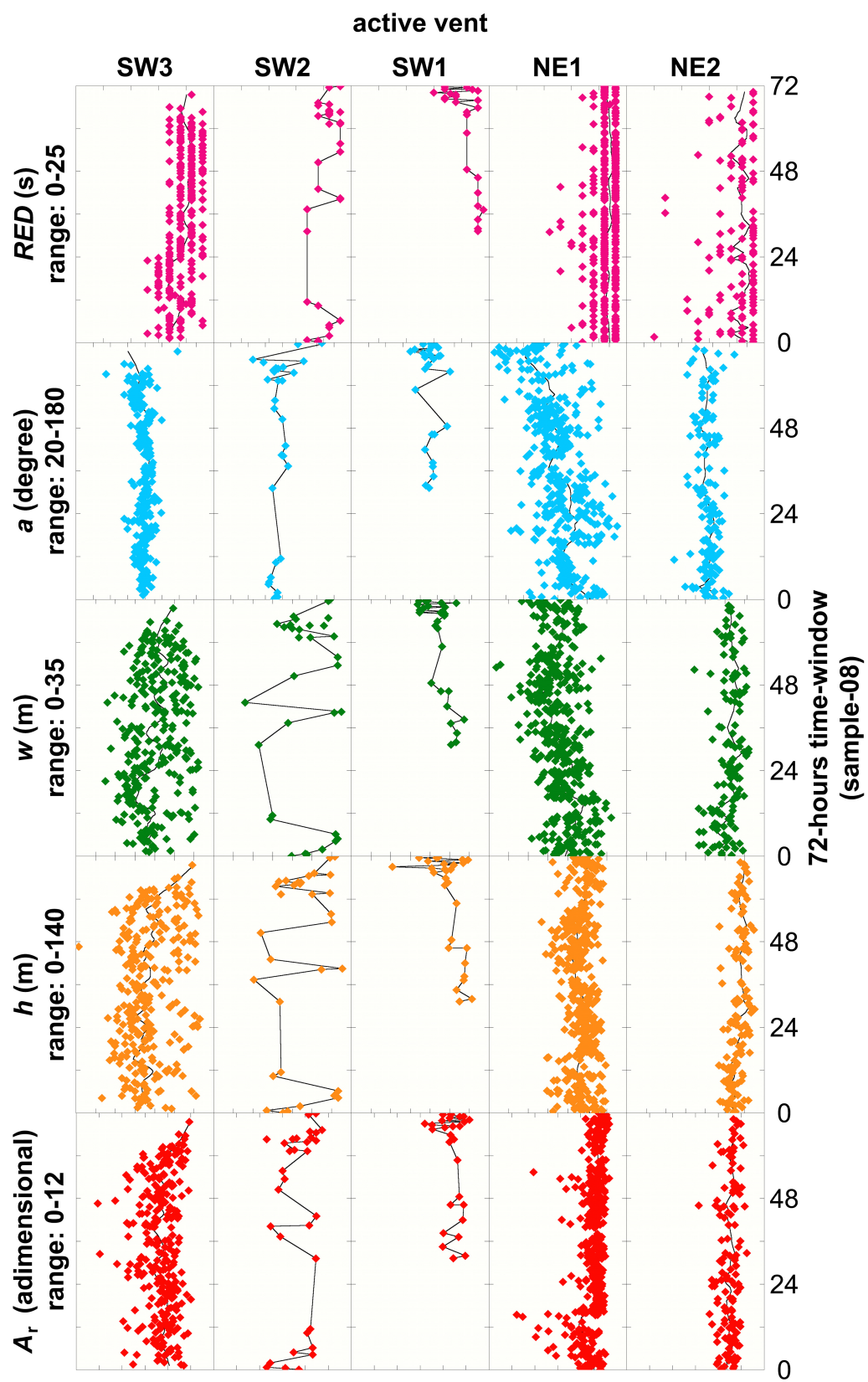
APPENDIX A – ENLARGED VERSIONS OF TIME WINDOW PLOTS

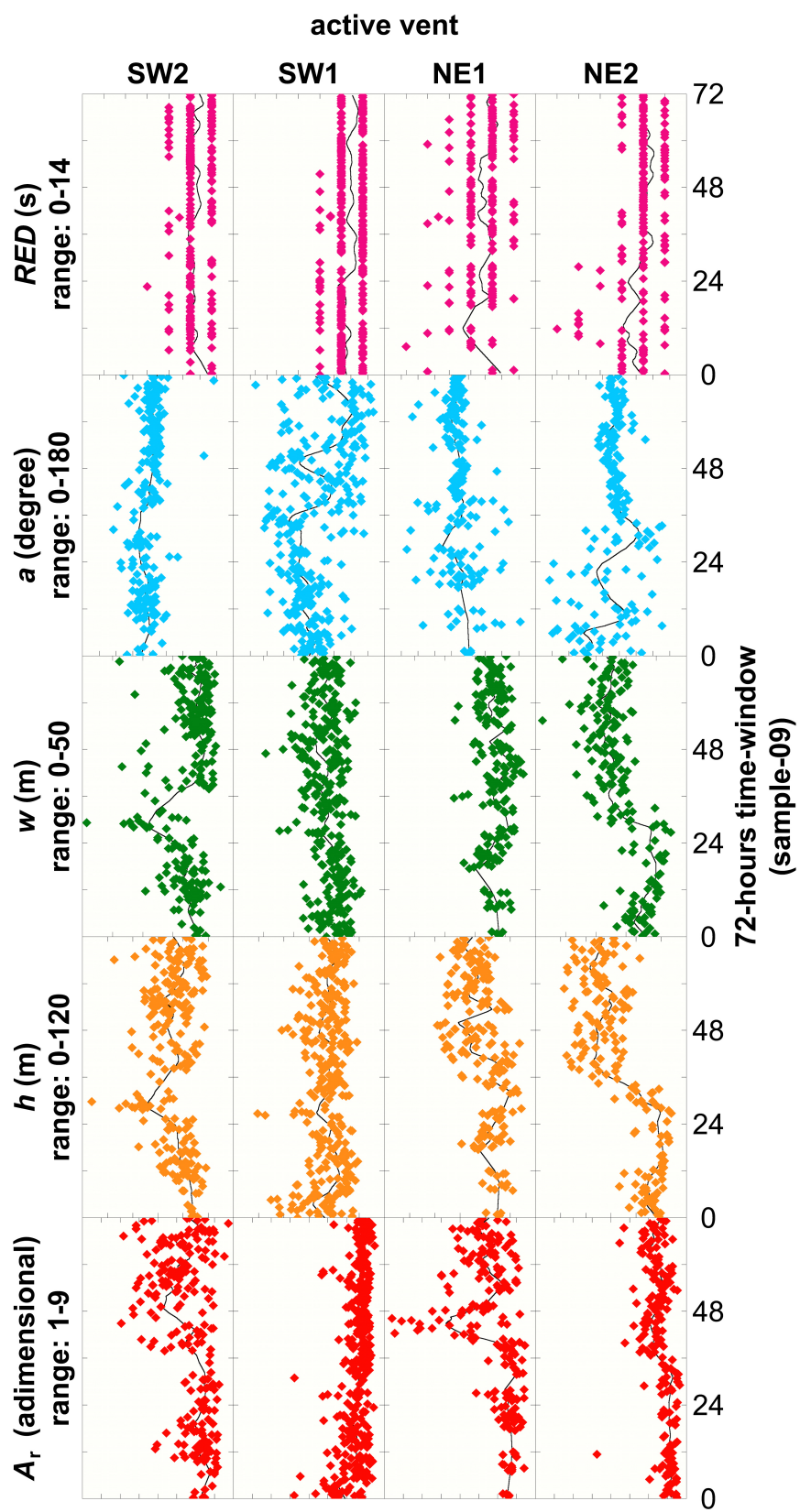
In this section we report the enlarged versions of the plot shown in Fig. 2.5, i.e. the evolution of the explosion jet parameters during the five 72-hours time-windows (i.e., *sample-05*, *sample-06*, *sample-07*, *sample-08*, and *sample-09*), which are reported in each plot. The y-axis scale range varies from case to case and is reported on top of each plot column. Time and spatial error is ± 2 s and ± 0.87 m, respectively.











APPENDIX B – REYNOLDS AND STOKES

NUMBERS AT STROMBOLI

Using equation (2), we estimated the order of magnitude of Re at the Stromboli vents (Table B.1). The gas density ranges between 0.204 and 0.297 kg/m³, calculated based on the ideal gas law:

$$\rho = \frac{MP_{atm}}{RT_g}, \quad (B.1)$$

where M is the molar mass, P_{atm} is the atmospheric pressure at the altitude of the Stromboli crater terrace (90442.93 Pa), R is the universal gas constant (8.314 J mol⁻¹ K⁻¹), and T_g is the gas temperature (between 1023 and 1273 K). Regarding the value of M , we assume two different gas mixtures, corresponding to gas measurements at Stromboli volcano (Aiuppa et al. 2010; Burton et al. 2007), with 64% H₂O, 33% CO₂ and 3% SO₂ for the first one, and 80% H₂O, 17% CO₂ and 3% SO₂ for the second one (with M equal to 0.02798 and 0.02382 kg/mol, respectively). The flow velocity U ranges between 652.40 and 788.76 m/s, obtained using the following equation:

$$U = \sqrt{\frac{\gamma RT_g}{M}}, \quad (B.2)$$

while the characteristic linear dimension L used in this case is the vent diameter at Stromboli (assumed between 2 and 3 m based on literature; Chouet et al. 1974; Gaudin et al. 2014). As gas viscosity, we considered the viscosity μ_{mix} calculated for both the above mentioned gas mixtures using the Carr's formula:

$$\mu_{mix} = \frac{\sum(x_i \mu_i \sqrt{M_i})}{\sum(x_i \sqrt{M_i})}, \quad (B.3)$$

where x_i , μ_i , and M_i are the molar fraction, the viscosity, and the molar mass of a specific

component i (i.e. H₂O, CO₂, or SO₂) of a determined gas mixture, respectively. We estimated the viscosities of the specific components at gas temperature T_g based on the equation (4). The μ_{mix} value ranges between 3.91×10^{-5} and 4.77×10^{-5} Pa s, and between 3.88×10^{-5} and 4.78×10^{-5} Pa s for the two above mentioned gas mixtures, respectively.

Introducing the values of this section in equations (5), (6), and (7), we estimated the St for Stromboli (Table B.1). The density (1200 kg/m³), diameter (between 0.05 and 0.369 m), and velocity (between 62 and 405 m/s) of the particles are assumed based on literature (Ripepe et al. 1993; Lautze and Houghton 2007; Taddeucci et al. 2012b; Gaudin et al. 2014).

Table B.1 Summary of the non-dimensional Reynolds, Reynolds of the particle, and Stokes numbers estimated for Stromboli.

Reynolds number Re	Reynolds number of particle Re_p	Stokes number St
$5.55 \times 10^6 - 1.81 \times 10^7$	$5.27 \times 10^4 - 2.06 \times 10^6$	20.11 – 95594.22

APPENDIX C – DERIVATION OF MACH NUMBER AND T FOR EQUATION (6)

For the Re and St calculation at the exit, U is calculated as follows. From the universal gas equation for ideal gases, we get:

$$PV = mRT, \quad (C.1)$$

where P is the absolute pressure, V is the volume of gas, m is the mass contained in V , R is the specific gas constant (i.e., $287.058 \text{ J Kg}^{-1} \text{ K}^{-1}$ for dry air), and T is the absolute temperature (everything in SI units). We can get that:

$$m = \frac{PV}{RT}. \quad (C.2)$$

We know that the mass in the whole tube at the beginning and at the end is the same, so that:

$$m_{final} = m_{pressurized} + m_{ambient}. \quad (C.3)$$

When we consider the initial mass contained in the pressurized side (i.e. $m_{pressurized}$) and compute the final pressure in the whole tube system (i.e. m_{final}), we have to take the mass contained in the ambient tube (i.e. $m_{ambient}$) into consideration. If we do not add it, we assume that in the other side of the diaphragm there is no air. We could write this formula in the form of pressures and temperatures, where the index “ f ” refers to the final quantities, “1” to pressurized and “2” to the rest of the tube at ambient pressure:

$$\frac{P_f V_f}{RT_f} = \frac{P_1 V_1}{RT_1} + \frac{P_2 V_2}{RT_2}. \quad (C.4)$$

We can take R away, just by multiplying everywhere by R :

$$\frac{P_f V_f}{T_f} = \frac{P_1 V_1}{T_1} + \frac{P_2 V_2}{T_2}. \quad (\text{C.5})$$

Now we have two unknowns: P_f and T_f (the fluid will expand and lower the pressure, but it will also cool down and the temperature will decrease). We can use the isentropic relations:

$$\frac{T_f}{T_2} = \left(\frac{P_f}{P_2} \right)^{\frac{\gamma-1}{\gamma}}. \quad (\text{C.6})$$

Hence, by multiplying and dividing by T_2 the first member of (C.5) and replacing with (C.6), we obtain:

$$\frac{P_f V_f T_2}{T_f T_2} = \frac{P_1 V_1}{T_1} + \frac{P_2 V_2}{T_2}, \quad (\text{C.7})$$

$$\frac{P_f V_f}{T_2} \left(\frac{P_2}{P_f} \right)^{\frac{\gamma-1}{\gamma}} = \frac{P_1 V_1}{T_1} + \frac{P_2 V_2}{T_2}, \quad (\text{C.8})$$

where the only unknown is P_f . Since the experiments are carried out at ambient temperature, $T_1 = T_2$, accordingly:

$$\frac{P_f V_f}{T_2} \left(\frac{P_2}{P_f} \right)^{\frac{\gamma-1}{\gamma}} = \frac{P_1 V_1 + P_2 V_2}{T_2}, \quad (\text{C.9})$$

$$P_f V_f \left(\frac{P_2}{P_f} \right)^{\frac{\gamma-1}{\gamma}} = P_1 V_1 + P_2 V_2, \quad (\text{C.10})$$

$$\frac{P_f}{P_f^{\frac{\gamma-1}{\gamma}}} = \frac{P_1 V_1 + P_2 V_2}{V_f (P_2)^{\frac{\gamma-1}{\gamma}}}, \quad (\text{C.11})$$

$$(P_f)^{\frac{1}{\gamma}} = \frac{P_1 V_1 + P_2 V_2}{V_f(P_2)^{\frac{\gamma-1}{\gamma}}}, \quad (\text{C.12})$$

$$P_f = \left(\frac{P_1 V_1 + P_2 V_2}{V_f(P_2)^{\frac{\gamma-1}{\gamma}}} \right)^{\gamma}. \quad (\text{C.13})$$

Having P_f , we can use again the formula (C.6) to resolve T_f . Now we have the state of the air inside the whole tube system by having the same mass as at the beginning, but having all air with the same pressure and the same temperature by leaving it in equilibrium (expanding). About the gas velocities, from the pressure ratio we can get the Mach number (Ma):

$$Ma = \sqrt{\frac{2}{\gamma - 1} \left(\left(\frac{P_f}{P_{amb}} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right)}, \quad (\text{C.14})$$

where P_{amb} is the ambient pressure. From Ma , we can get the temperature because of the motion of the fluid:

$$T = \frac{T_f}{1 + Ma^2 \left(\frac{\gamma - 1}{2} \right)}, \quad (\text{C.15})$$

and having Ma and T , we derive the velocity by equation (6).

REFERENCES

- Abramoff MD, Magelhaes PJ, Ram SJ (2004) Image processing with ImageJ. *Biophoton Int* 11:36–42. <http://www.imagescience.org/meijering/publications/download/bio2004.pdf>
- Aiuppa A, Federico C, Giudice G, Giuffrida G, Guida R, Gurrieri S, Liuzzo M, Moretti R, Papale P (2009) The 2007 eruption of Stromboli Volcano: insights from real-time measurement of the volcanic gas plume CO₂/SO₂ ratio. *J Volcanol Geotherm Res* 182:221–230. <https://doi.org/10.1016/j.jvolgeores.2008.09.013>
- Alatorre-Ibargüengoitia MA, Scheu B, Dingwell DB, Delgado-Granados H, Taddeucci J (2010) Energy consumption by magmatic fragmentation and pyroclast ejection during Vulcanian eruptions. *Earth Planet Sci Lett* 291:60–69. <https://doi.org/10.1016/j.epsl.2009.12.051>
- Alatorre-Ibargüengoitia MA, Scheu B, Dingwell DB (2011) Influence of the fragmentation process on the dynamics of Vulcanian eruptions: an experimental approach. *Earth Planet Sci Lett* 302:51–59. <https://doi.org/10.1016/j.epsl.2010.11.045>
- Alidibirov MA (1994) A model for viscous magma fragmentation during volcanic blasts. *Bull Volcanol* 56:459–465. <https://doi.org/10.1007/BF00302827>
- Alidibirov M, Dingwell DB (1996a) Magma fragmentation by rapid decompression. *Nature* 380:146–148. <https://doi.org/10.1038/380146a0>
- Alidibirov M, Dingwell DB (1996b) An experimental facility for the investigation of magma fragmentation by rapid decompression. *Bull Volcanol* 58:411–416. <https://doi.org/10.1007/s004450050149>
- Alidibirov M, Dingwell DB (2000) Three fragmentation mechanisms for highly viscous magma under rapid decompression. *J Volcanol Geotherm Res* 100:413–421. [https://doi.org/10.1016/S0377-0273\(00\)00149-9](https://doi.org/10.1016/S0377-0273(00)00149-9)
- Andronico D, Pistolesi M (2010) The November 2009 paroxysmal explosions at Stromboli. *J Volcanol Geotherm Res* 196:120–125. <https://doi.org/10.1016/j.jvolgeores.2010.06.005>
- Andronico D, Corsaro RA, Cristaldi A, Polacci M (2008) Characterizing high energy explosive eruptions at Stromboli Volcano using multidisciplinary data: an example from the 9 January 2005 explosion. *J Volcanol Geotherm Res* 176:541–550. <https://doi.org/10.1016/j.jvolgeores.2008.05.011>

- Andronico D, Taddeucci J, Cristaldi A, Miraglia M, Scarlato P, Gaeta M (2013) The 15 March 2007 paroxysm of Stromboli: video-image analysis, and textural and compositional features of the erupted deposit. *Bull Volcanol* 75:1–19. <https://doi.org/10.1007/s00445-013-0733-2>
- Arciniega-Ceballos A, Alatorre-Ibargüengoitia MA, Scheu B, Dingwell DB (2015) Analysis of source characteristics of experimental gas burst and fragmentation explosions generated by rapid decompression of volcanic rocks. *J Geophys Res* 120:5104–5116. <https://doi.org/10.1002/2014JB011810>
- Auer A, Martin U, Németh K (2007) The Fekete-hegy (Balaton Highland Hungary) “soft-substrate” and “hard-substrate” maar volcanoes in an aligned volcanic complex – implications for vent geometry, subsurface stratigraphy and the palaeoenvironmental setting. *J Volcanol Geotherm Res* 159:225–245. <https://doi.org/10.1016/j.jvolgeores.2006.06.008>
- Barberi F, Rosi M, Sodi A (1993) Volcanic hazard assessment at Stromboli based on review of historical data. *Acta Vulcanol* 3:173–187.
- Barberi F, Civetta L, Rosi M, Scandone R (2009) Chronology of the 2007 eruption of Stromboli and the activity of the Scientific Synthesis Group. *J Volcanol Geotherm Res* 182:123–130. <https://doi.org/10.1016/j.jvolgeores.2008.09.019>
- Bertagnini A, Coltelli M, Landi P, Pompilio M, Rosi M (1999) Violent explosions yield new insights into dynamics of Stromboli Volcano. *EOS Trans AGU* 80:633–636. <https://doi.org/10.1029/99EO00415>
- Bertagnini A, Métrich N, Francalanci L, Landi P, Tommasini S, Conticelli S (2008) Volcanology and magma geochemistry of the present-day activity: constraints on the feeding system. In: Calvari S, Inguaggiato S, Puglisi G, Ripepe M, Rosi M (eds) *The Stromboli Volcano: an integrated study of the 2002–2003 eruption*. *Am Geophys Union Geophys Mon* 182:19–37. <https://doi.org/10.1029/182GM04>
- Blackburn EA, Wilson L, Sparks RSJ (1976) Mechanisms and dynamics of Strombolian activity. *J Geol Soc London* 132:429–440. <https://doi.org/10.1144/gsjgs.132.4.0429>
- Boccaletti M, Nicolich R, Tortorici L (1984) The Calabrian Arc and the Ionian Sea in the dynamic evolution of the Central Mediterranean. *Mar Geol* 55:219–240. [https://doi.org/10.1016/0025-3227\(84\)90070-7](https://doi.org/10.1016/0025-3227(84)90070-7)
- Bombrun M, Harris A, Gurioli L, Battaglia J, Barra V (2015) Anatomy of a strombolian eruption: inferences from particle data recorded with thermal video. *J Geophys Res* 120:2367–2387. <https://doi.org/10.1002/2014JB011556>

- Bonaccorso A, Calvari S, Garfi G, Lodato L, Patanè D (2003) Dynamics of the December 2002 flank failure and tsunami at Stromboli Volcano inferred by volcanological and geophysical observations. *Geophys Res Lett* 30:1941–1944. <https://doi.org/10.1029/2003GL017702>
- Bonadonna C, Costa A (2013) Modeling of tephra sedimentation from volcanic plumes. In: Fagents S, Gregg T, Lopes R (eds) *Modeling volcanic processes: the physics and mathematics of volcanism*. Cambridge University Press, Cambridge, pp 173–202.
- Bosman A, Chiocci FL, Romagnoli C (2009), Morpho-structural setting of Stromboli Volcano revealed by high-resolution bathymetry and backscatter data of its submarine portions. *Bull Volcanol* 71:1007–1019. <https://doi.org/10.1007/s00445-009-0279-5>
- Brenna M, Németh K, Cronin SJ, Sohn YK, Smith IEM, Wijbrans J (2015) Co-located monogenetic eruptions ~200 kyr apart driven by tapping vertically separated mantle source regions, Chagwido, Jeju Island, Republic of Korea. *Bull Volcanol* 77:43. <https://doi.org/10.1007/s00445-015-0928-9>
- Burgisser A, Bergantz GW, Breidenthal RE (2005) Addressing complexity in laboratory experiments: the scaling of dilute multiphase flows in magmatic systems. *J Volcanol Geotherm Res* 141:245–265. <https://doi.org/10.1016/j.jvolgeores.2004.11.001>
- Burton M, Allard P, Muré F, La Spina A (2007) Magmatic gas composition reveals the source depth of slug-driven Strombolian explosive activity. *Science* 317:227–230. <https://doi.org/10.1126/science.1141900>
- Calvari S, Spampinato L, Lodato L, Harris AJL, Patrick MR, Dehn J, Burton MR, Andronico D (2005) Chronology and complex volcanic processes during the 2002–2003 flank eruption at Stromboli Volcano (Italy) reconstructed from direct observations and surveys with a handheld thermal camera. *J Geophys Res* 110:B02201. <https://doi.org/10.1029/2004JB003129>
- Calvari S, Lodato L, Steffke A, Cristaldi A, Harris AJL, Spampinato L, Boschi E (2010) The 2007 Stromboli eruption: event chronology and effusion rates using thermal infrared data. *J Geophys Res* 115:B04201. <https://doi.org/10.1029/2009JB006478>
- Calvari S, Bonaccorso A, Madonia P, Neri M, Liuzzo M, Salerno GG, Behncke B, Caltabiano T, Cristaldi A, Giuffrida G, La Spina A, Marotta E, Ricci T, Spampinato L (2014) Major eruptive style changes induced by structural modifications of a shallow conduit system: the 2007–2012 Stromboli case. *Bull Volcanol* 76:841. <https://doi.org/10.1007/s00445-014-0841-7>
- Cannata A, Sciutto M, Spampinato L, Spina L (2011) Insights into explosive activity at

- closely-spaced eruptive vents using infrasound signals: example of Mt. Etna 2008 eruption. *J Volcanol Geotherm Res* 208:1–11. <https://doi.org/10.1016/j.jvolgeores.2011.09.003>
- Capponi A, Taddeucci J, Scarlato P, Palladino DM (2016) Recycled ejecta modulating Strombolian explosions. *Bull Volcanol* 78:1–13. <https://doi.org/10.1007/s00445-016-1001-z>
- Carapezza ML, Inguaggiato S, Brusca L, Longo M (2004) Geochemical precursors of the activity of an open-conduit volcano: the Stromboli 2002–2003 eruptive events. *Geophys Res Lett* 31:L07620. <https://doi.org/10.1029/2004GL019614>
- Carcano S, Bonaventura L, Esposti Ongaro T, Neri A (2013) A semi-implicit, second order accurate numerical model for multiphase underexpanded volcanic jets. *Geosci Model Dev Discuss* 6:399–452. <https://doi.org/10.5194/gmdd-6-399-2013>
- Carcano S, Esposti Ongaro T, Bonaventura L, Neri A (2014) Influence of grain-size distribution on the dynamics of underexpanded volcanic jets. *J Volcanol Geotherm Res* 285:60–80. <https://doi.org/10.1016/j.jvolgeores.2014.08.003>
- Cashman KV, Sparks RSJ (2013) How volcanoes work: a 25 year perspective. *Geol Soc Am Bull* 125:664–690. <https://doi.org/10.1130/B30720.1>
- Cashman KV, Scheu B (2015) Magmatic fragmentation. In: Sigurdsson H, Houghton B, Rymer H, Stix J, McNutt S (eds) *The encyclopedia of volcanoes* 2nd edn. Academic Press, Amsterdam, pp 257–264. <https://doi.org/10.1016/B978-0-12-385938-9.00025-0>
- Chouet B (2003) Volcano seismology. *PAGEoph* 160:739–788. <https://doi.org/10.1007/PL00012556>
- Chouet B, Hamisevicz N, McGetchin TR (1974) Photoballistics of volcanic jet activity at Stromboli, Italy. *J Geophys Res* 79:4961–4976. <https://doi.org/10.1029/JB079i032p04961>
- Chouet B, Dawson P, Ohminato T, Martini M, Saccorotti G, Giudicepietro F, De Luca G, Milana G, Scarpa R (2003) Source mechanisms of explosions at Stromboli Volcano, Italy, determined from moment-tensor inversions of very-long-period data. *J Geophys Res* 108:2019. <https://doi.org/10.1029/2002JB001919>
- Chouet B, Dawson P, Martini M (2008) Shallow-conduit dynamics at Stromboli Volcano, Italy, imaged from waveform inversions. In: Lane SJ, Gilbert JS (eds) *Fluid motions in volcanic conduits: a source of seismic and acoustic signals*. *Geol Soc London Spec Pub* 307:57–84. <https://doi.org/10.1144/SP307.5>
- Chouet BA, Dawson PB, James M, Lane SJ (2010) Seismic source mechanism of degassing

- bursts at Kilauea Volcano, Hawaii: results from waveform inversion in the 10–50 s band. *J Geophys Res* 115:B09311. <https://doi.org/10.1029/2009JB006661>
- Cigala V, Kueppers U, Peña Fernández JJ, Taddeucci J, Sesterhenn J, Dingwell DB (2017) The dynamics of volcanic jets: temporal evolution of particles exit velocity from shock-tube experiments. *J Geophys Res* 122:6031–6045. <https://doi.org/10.1002/2017JB014149>
- Cigala V, Arciniega A, Salvatore V, Taddeucci J, Kueppers U, Dingwell DB (2018) Particles in motion: coupling high-resolution videos and geophysical techniques in the lab to decipher pyroclast ejection dynamics. Vol. 20, EGU2018–15365, EGU General Assembly, Vienna, Austria, 8–13 April 2018.
- Clarke AB (2013) Unsteady explosive activity: Vulcanian eruptions. In: Fagents SA, Gregg TKP, Lopes RMC (eds) *Modeling volcanic processes. The physics and mathematics of volcanism*. Cambridge University Press, Cambridge, pp 129–152.
- Cocomello S (2013) Modellazione analogica dell'attività vulcanica esplosiva stromboliana. Master's degree thesis, Sapienza University of Rome, Rome, Italy.
- De Astis G, Ventura G, Vilardo G (2003) Geodynamic significance of the Aeolian volcanism (Southern Tyrrhenian Sea, Italy) in light of structural, seismological, and geochemical data. *Tectonics* 22:1040. <https://doi.org/10.1029/2003TC001506>
- Del Bello E, Llewellyn EW, Taddeucci J, Scarlato P, Lane SJ (2012) An analytical model for gas overpressure in slug-driven explosions: insights into Strombolian volcanic eruptions. *J Geophys Res* 117:B02206. <https://doi.org/10.1029/2011JB008747>
- Del Bello E, Lane SJ, James MR, Llewellyn EW, Taddeucci J, Scarlato P, Capponi A (2015) Viscous plugging can enhance and modulate explosivity of strombolian eruptions. *Earth Planet Sc Lett* 423:210–218. <https://doi.org/10.1016/j.epsl.2015.04.034>
- Delle Donne D, Ripepe M (2012) High-frame rate thermal imagery of Strombolian explosions: implications for explosive and infrasonic source dynamics. *J Geophys Res* 117:B09206. <https://doi.org/10.1029/2011JB008987>
- Di Vito MA, Arienzo I, Braia G, Civetta L, D'Antonio M, Di Renzo V, Orsi G (2011) The Averno 2 fissure eruption: a recent small-size explosive event at the Campi Flegrei Caldera (Italy). *Bull Volcanol* 73:295–320. <https://doi.org/10.1007/s00445-010-0417-0>
- Douillet GA, Rasmussen KR, Kueppers U, Castro DL, Merrison JP, Iverson JJ, Dingwell DB (2014) Saltation threshold for pyroclasts at various bedslopes: wind tunnel measurements. *J Volcanol Geotherm Res* 278–279:14–24. <https://doi.org/10.1016/j.jvolgeothermres.2014.05.001>

- Dubosclard G, Donnadieu F, Allard P, Cordesses R, Hervier C, Coltelli M, Privitera E, Kornprobst J (2004) Doppler radar sounding of volcanic eruption dynamics at Mount Etna. *Bull Volcanol* 66:443–456. <https://doi.org/10.1007/s00445-003-0324-8>
- Dufek J, Manga M, Patel A (2012) Granular disruption during explosive volcanic eruptions. *Nat Geosci* 5(8):561–564. <https://doi.org/10.1038/ngeo1524>
- Dürig T, Gudmundsson MT, Dellino P (2015) Reconstruction of the geometry of volcanic vents by trajectory tracking of fast ejecta - the case of the Eyjafjallajökull 2010 eruption (Iceland). *Earth Planets Space* 67:64. <https://doi.org/10.1186/s40623-015-0243-x>
- Elghobashi S, Truesdell GC (1993) On the two-way interaction between homogeneous turbulence and dispersed solid particles. I: Turbulence modification. *Phys Fluids A* 5:1790–1801. <https://doi.org/10.1063/1.858854>
- Fowler AC, Scheu B, Lee WT, McGuinness MJ (2010) A theoretical model of the explosive fragmentation of vesicular magma. *Proc R Soc A* 466:731–752. <http://dx.doi.org/10.1098/rspa.2009.0382>
- Francalanci L, Tommasini S, Conticelli S (2004) The volcanic activity of Stromboli in the 1906–1998 AD period: mineralogical, geochemical and isotope data relevant to the understanding of the plumbing system. *J Volcanol Geotherm Res* 131:179–211. [https://doi.org/10.1016/S0377-0273\(03\)00362-7](https://doi.org/10.1016/S0377-0273(03)00362-7)
- Francalanci L, Davies GR, Lustenmhower W, Tommasini S, Mason PRD, Conticelli S (2005) Intra-grain Sr isotope evidence for crystal recycling and multiple magma reservoirs in the recent activity of Stromboli Volcano, Southern Italy. *J Petrol* 46:1997–2021. <https://doi.org/10.1093/petrology/egi045>
- Gardner JE, Thomas RME, Jaupart C, Tait S (1996) Fragmentation of magma during Plinian volcanic eruptions. *Bull Volcanol* 58:144–162. <https://doi.org/10.1007/s004450050132>
- Gaudin D, Taddeucci J, Scarlato P, Moroni M, Freda C, Gaeta M, Palladino DM (2014) Pyroclast tracking velocimetry illuminates bomb ejection and explosion dynamics at Stromboli (Italy) and Yasur (Vanuatu) volcanoes. *J Geophys Res* 119:5384–5397. <https://doi.org/10.1002/2014JB011096>
- Gaudin D, Taddeucci J, Scarlato P, Del Bello E, Ricci T, Orr T, Houghton B, Harris A, Rao S, Bucci A (2017) Integrating puffing and explosions in a general scheme for Strombolian-style activity. *J Geophys Res* 122:1860–1875. <https://doi.org/10.1002/>

- Geshi N, Kusumoto S, Gudmundsson A (2010) Geometric difference between non-feeder and feeder dikes. *Geology* 38:195–198. <https://doi.org/10.1130/G30350.1>
- Geshi N, Németh K, Oikawa T (2011) Growth of phreatomagmatic explosion craters: a model inferred from Suoana crater in Miyakejima Volcano, Japan. *J Volcanol Geotherm Res* 20:30–38. <https://doi.org/10.1016/j.jvolgeores.2010.11.012>
- Gonnerman HM, Manga M (2003) Explosive volcanism may not be an inevitable consequence of magma fragmentation. *Nature* 426:432–435. <https://doi.org/10.1038/nature02138>
- Gouhier M, Donnadieu F (2011) Systematic retrieval of ejecta velocities and gas fluxes at Etna volcano using L-Band Doppler radar. *Bull Volcanol* 73:1139–1145. <https://doi.org/10.1007/s00445-011-0500-1>
- Graettinger AH, Valentine GA, Sonder I (2015) Circum-crater variability of deposits from discrete, laterally and vertically migrating volcanic explosions: experimental evidence and field implications. *J Volcanol Geotherm Res* 308:61–69. <https://doi.org/10.1016/j.jvolgeores.2015.10.019>
- Gurioli L, Harris AJL, Colò L, Bernard J, Favalli M, Ripepe M, Andronico D (2013) Classification, landing distribution, and associated flight parameters for a bomb field emplaced during a single major explosion at Stromboli, Italy. *Geology* 41:559–562. <https://doi.org/10.1130/G33967.1>
- Gurioli L, Colò L, Bollasina AJ, Harris AJL, Whittington A, Ripepe M (2014) Dynamics of Strombolian explosions: inferences from field and laboratory studies of erupted bombs from Stromboli Volcano. *J Geophys Res* 119:319–345. <https://doi.org/10.1002/2013JB010355>
- Harris AJL, Ripepe M (2007a) Temperature and dynamics of degassing at Stromboli. *J Geophys Res* 112:B03205. <https://doi.org/10.1029/2006JB004393>
- Harris AJL, Ripepe M (2007b) Synergy of multiple geophysical approaches to unravel explosive eruption conduit and source dynamics – a case study from Stromboli. *Chemie der Erde – Geochem* 67:1–35. <https://doi.org/10.1016/j.chemer.2007.01.003>
- Harris AJL, Ripepe M, Hughes EA (2012) Detailed analysis of particle launch velocities, size distributions and gas densities during normal explosions at Stromboli. *J Volcanol Geotherm Res* 231–232:109–131. <https://doi.org/10.1016/j.jvolgeores.2012.02.012>
- Houghton BF, Gonnermann HM (2008) Basaltic explosive volcanism: constraints from deposits and models. *Chemie der Erde – Geochem* 68:117–140. <https://doi.org/>

[10.1016/j.chemer.2008.04.002](https://doi.org/10.1016/j.chemer.2008.04.002)

- Houghton BF, Wilson CJN, Del Carlo P, Coltelli M, Sable JE, Carey R (2004) The influence of conduit processes on changes in style of basaltic Plinian eruptions: Tarawera 1886 and Etna 122 BC. *J Volcanol Geotherm Res* 137:1–14. <https://doi.org/10.1016/j.jvolgeores.2004.05.009>
- Ichihara M, Rittel D, Sturtevant B (2002) Fragmentation of a porous viscoelastic material: implications to magma fragmentation. *J Geophys Res* 107:2229. <https://doi.org/10.1029/2001JB000591>
- Inguaggiato S, Vita F, Rouwet D, Bobrowski N, Morici S, Sollami A (2011) Geochemical evidence of the renewal of volcanic activity inferred from CO₂ soil and SO₂ plume fluxes: the 2007 Stromboli eruption (Italy). *Bull Volcanol* 73:443–456. <https://doi.org/10.1007/s00445-010-0442-z>
- James MR, Lane SJ, Chouet B, Gilbert JS (2004) Pressure changes associated with the ascent and bursting of gas slugs in liquid-filled vertical and inclined conduits. *J Volcanol Geotherm Res* 129:61–82. [https://doi.org/10.1016/S0377-0273\(03\)00232-4](https://doi.org/10.1016/S0377-0273(03)00232-4)
- James MR, Lane SJ, Corder SB (2008) Modelling the rapid near-surface expansion of gas slugs in low-viscosity magmas. In: Lane SJ and Gilbert JS (eds) *Fluid motions in volcanic conduits: a source of seismic and acoustic signals*. Geol Soc London Special Pub 307:147–167. <https://doi.org/10.1144/SP307.9>
- James MR, Lane SJ, Wilson L, Corder SB (2009) Degassing at low magma-viscosity volcanoes: quantifying the transition between passive bubble-burst and Strombolian eruption. *J Volcanol Geotherm Res* 180:81–88. <https://doi.org/10.1016/j.jvolgeores.2008.09.002>
- Jaupart C, Vergnolle S (1988) Laboratory models of Hawaiian and Strombolian eruptions. *Nature* 331:58–60. <https://doi.org/10.1038/331058a0>
- Johnson J (2003) Interpretation and utility of infrasonic records from erupting volcanoes. *J Volcanol Geotherm Res* 121:15–63. [https://doi.org/10.1016/S0377-0273\(02\)00409-2](https://doi.org/10.1016/S0377-0273(02)00409-2)
- Keating GN, Valentine GA, Krier DJ, Perry FV (2008) Shallow plumbing systems for small-volume basaltic volcanoes. *Bull Volcanol* 70:563–582. <https://doi.org/10.1007/s00445-007-0154-1>
- Kennedy B, Spieler O, Scheu B, Kueppers U, Taddeucci J, Dingwell DB (2005) Conduit implosion during Vulcanian eruptions. *Geology* 33:581–584. <https://doi.org/10.1130/G21488.1>
- Kereszturi G, Jordan G, Németh K, Dóniz-Páez JF (2012) Syn-eruptive morphometric

- variability of monogenetic scoria cones. *Bull Volcanol* 74:2171–2185. <https://doi.org/10.1007/s00445-012-0658-1>
- Kieffer SW (1984) Factors governing the structure of volcanic jets. In: Explosive volcanism: inception, evolution, and hazards. National Academy Press, Washington DC, pp 143–157.
- Kieffer SW, Sturtevant B (1984) Laboratory studies of volcanic jets. *J Geophys Res* 89:8253–8268. <https://doi.org/10.1029/JB089iB10p08253>
- Kósik S, Németh K, Kereszturi G, Procter JN, Zellmer GF, Geshi N (2016) Phreatomagmatic and water-influenced Strombolian eruptions of a small-volume parasitic cone complex on the southern ringplain of Mt. Ruapehu, New Zealand: facies architecture and eruption mechanisms of the Ohakune Volcanic Complex controlled by an unstable fissure eruption. *J Volcanol Geotherm Res* 327:99–115. <https://doi.org/10.1016/j.jvolgeores.2016.07.005>
- Kremers S, Wassermann J, Meier K, Pelties C, van Driel M, Vasseur J, Hort M (2013) Inverting the source mechanism of Strombolian explosions at Mt. Yasur, Vanuatu, using a multi-parameter dataset. *J Volcanol Geotherm Res* 262:104–122. <https://doi.org/10.1016/j.jvolgeores.2013.06.007>
- Kueppers U, Scheu B, Spieler O, Dingwell DB (2006a) Fragmentation efficiency of explosive volcanic eruptions: a study of experimentally generated pyroclasts. *J Volcanol Geotherm Res* 153:125–135. <https://doi.org/10.1016/j.jvolgeores.2005.08.006>
- Kueppers U, Perugini D, Dingwell DB (2006b) “Explosive energy” during volcanic eruptions from fractal analysis of pyroclasts. *Earth Planet Sci Lett* 248:800–807. <https://doi.org/10.1016/j.epsl.2006.06.033>
- Landi P, Métrich N, Bertagnini A, Rosi M (2008) Recycling and “re-hydration” of degassed magma inducing transient dissolution/crystallization events at Stromboli (Italy). *J Volcanol Geotherm Res* 174:325–336. <https://doi.org/10.1016/j.jvolgeores.2008.02.013>
- Landi P, Corsaro RA, Francalanci L, Civetta L, Miraglia L, Pompilio M, Tesoro R (2009) Magma dynamics during the 2007 Stromboli eruption (Aeolian Islands, Italy): mineralogical, geochemical and isotopic data. *J Volcanol Geotherm Res* 182:255–268. <https://doi.org/10.1016/j.jvolgeores.2008.11.010>
- Landi P, Marchetti E, La Felice S, Ripepe M, Rosi M (2011) Integrated petrochemical and geophysical data reveals thermal distribution of the feeding conduits at Stromboli Volcano, Italy. *Geophys Res Lett* 38:L08305. <https://doi.org/10.1029/2010GL046296>

- Lautze NC, Houghton BF (2005) Physical mingling of magma and complex eruption dynamics in the shallow conduit at Stromboli Volcano, Italy. *Geology* 33:425–428. <https://doi.org/10.1130/G21325.1>
- Lautze NC, Houghton BF (2007) Linking variable explosion style and magma textures during 2002 at Stromboli Volcano, Italy. *Bull Volcanol* 69:445–460. <https://doi.org/10.1007/s00445-006-0086-1>
- Leduc L, Gurioli L, Harris A, Colò L, Rose-Koga EF (2015) Types and mechanisms of strombolian explosions: characterization of a gas-dominated explosion at Stromboli. *Bull Volcanol* 77:1–15. <https://doi.org/10.1007/s00445-014-0888-5>
- Marchetti E, Harris AJL (2008) Trends in activity at Pu'u 'O'o during 2001–2003: insights from the continuous thermal record. In: Lane SJ and Gilbert JS (eds) *Fluid motions in volcanic conduits: a source of seismic and acoustic signals*. Geol Soc London Spec Pub 307:85–101. <https://doi.org/10.1144/SP307.6>
- Marchetti E, Ripepe M (2005) Stability of the seismic source during effusive and explosive activity at Stromboli Volcano. *Geophys Res Lett* 32:L03307. <https://doi.org/10.1029/2004GL021406>
- Mercalli G (1907) *I vulcani attivi della terra: morfologia – dinamismo – prodotti – distribuzione geografica – cause*. Ulrico Hoepli, Milan, p. 421.
- Métrich N, Bertagnini A, Di Muro A (2010) Conditions of magma storage, degassing and ascent at Stromboli: new insights into the volcano plumbing system with inferences on the eruptive dynamics. *J Petrol* 51:603–626. <https://doi.org/10.1093/petrology/egp083>
- Morgado WAM, Oppenheim I (1997) Energy dissipation for quasielastic granular particle collisions. *Phys Rev E* 55:1940–1945. <https://doi.org/10.1103/PhysRevE.55.1940>
- Mori T, Burton M (2009) Quantification of the gas mass emitted during single explosions on Stromboli with the SO₂ imaging camera. *J Volcanol Geoth Res* 188:395–400. <https://doi.org/10.1016/j.jvolgeores.2009.10.005>
- Mueller S, Melnik O, Spieler O, Scheu B, Dingwell DB (2005) Permeability and degassing of dome lavas undergoing rapid decompression: an experimental determination. *Bull Volcanol* 67:526–538. <https://doi.org/10.1007/s00445-004-0392-4>
- Mueller S, Scheu B, Spieler O, Dingwell DB (2008) Permeability control on magma fragmentation. *Geology* 36:399–402. <https://doi.org/10.1130/G24605A.1>
- Németh K, Cronin SJ (2011) Drivers of explosivity and elevated hazard in basaltic fissure eruptions: the 1913 eruption of Ambrym Volcano, Vanuatu (SW-Pacific). *J Volcanol Geotherm Res* 201:194–209. <https://doi.org/10.1016/j.jvolgeores.2010.12.007>

- Neri M, Lanzafame G (2009) Structural features of the 2007 Stromboli eruption. *J Volcanol Geotherm Res* 182:137–144. <https://doi.org/10.1016/j.jvolgeores.2008.07.021>
- Ogden D (2011) Fluid dynamics in explosive volcanic vents and craters. *Earth Planet Sc Lett* 312:401–410. <https://doi.org/10.1016/j.epsl.2011.10.032>
- Oppenheimer C, Bani P, Calkins JA, Burton MR, Sawyer GM (2006) Rapid FTIR sensing of volcanic gases released by Strombolian explosions at Yasur volcano, Vanuatu. *Appl Phys B* 85:453–460. <https://doi.org/10.1007/s00340-006-2353-4>
- Ort MH, Carrasco-Núñez G (2009) Lateral vent migration during phreatomagmatic and magmatic eruptions at Tecuitlapa Maar, east-central Mexico. *J Volcanol Geotherm Res* 181:67–77. <https://doi.org/10.1016/j.jvolgeores.2009.01.003>
- Papale P (1999) Strain-induced magma fragmentation. *Nature* 397: 425–428. <https://doi.org/10.1038/17109>
- Parfitt EA (2004) A discussion of the mechanisms of explosive basaltic eruptions. *J Volcanol Geotherm Res* 134:77–107. <https://doi.org/10.1016/j.jvolgeores.2004.01.002>
- Parfitt EA, Wilson L (1995) Explosive volcanic-eruptions—IX. The transition between Hawaiian-style lava fountaining and Strombolian explosive activity. *Geophys J Int* 121:226–232. <https://doi.org/10.1111/j.1365-246X.1995.tb03523.x>
- Patrick MR, Harris AJL, Ripepe M, Dehn J, Rothery DA, Calvari S (2007) Strombolian explosive styles and source conditions: insights from thermal (FLIR) video. *Bull Volcanol* 69:769–784. <https://doi.org/10.1007/s00445-006-0107-0>
- Peccerillo A (2001) Geochemical similarities between the Vesuvius, Phlegraean Fields and Stromboli volcanoes: petrogenetic, geodynamic and volcanological implications. *Mineral Petrol* 73:93–105. <https://doi.org/10.1007/s007100170012>
- Pedrazzi D, Bolós X, Barde-Cabusson S, Martí J (2016) Reconstructing the eruptive history of a monogenetic volcano through a combination of fieldwork and geophysical surveys: the example of Puig d'Àdri (Garrotxa Volcanic Field). *J Geol Soc London* 173:875–888. <https://doi.org/10.1144/jgs2016-009>
- Pioli L, Azzopardi BJ, Cashman KV (2009) Controls on the explosivity of scoria cone eruptions: magma segregation at conduit junctions. *J Volcanol Geotherm Res* 186:407–415. <https://doi.org/10.1016/j.jvolgeores.2009.07.014>
- 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. *J Geophys Res* 116:B12206. <https://doi.org/10.1029/2011JB008527>

- Polacci M, Papale P, Del Seppia D, Giordano D, Romano C (2004) Dynamics of magma ascent and fragmentation in trachytic versus rhyolitic eruptions. *J Volcanol Geotherm Res* 131:93–108. [https://doi.org/10.1016/S0377-0273\(03\)00319-6](https://doi.org/10.1016/S0377-0273(03)00319-6)
- Renzulli A, Del Moro S, Menna M, Landi P, Piermattei M (2009) Transient processes in Stromboli's shallow basaltic system inferred from dolerite and magmatic breccia blocks erupted during the 5 April 2003 paroxysm. *Bull Volcanol* 71:795–813. <https://doi.org/10.1007/s00445-009-0265-y>
- Richard D, Scheu B, Mueller SP, Spieler O, Dingwell DB (2013) Outgassing: Influence on speed of magma fragmentation. *J Geophys Res* 118:862–877. <https://doi.org/10.1002/jgrb.50080>
- Ripepe M (1996) Evidence for gas influence on volcanic seismic signals at Stromboli. *J Volcanol Geotherm Res* 70:221–233. [https://doi.org/10.1016/0377-0273\(95\)00057-7](https://doi.org/10.1016/0377-0273(95)00057-7)
- Ripepe M, Marchetti E (2002) Array tracking of infrasonic sources at Stromboli volcano. *Geophys Res Lett* 29:2076. <https://doi.org/10.1029/2002GL015452>
- Ripepe M, Rossi M, Saccorotti G (1993) Image processing of explosive activity at Stromboli. *J Volcanol Geotherm Res* 54:335–351. [https://doi.org/10.1016/0377-0273\(93\)90071-X](https://doi.org/10.1016/0377-0273(93)90071-X)
- Ripepe M, Poggi P, Braun T, Gordeev E (1996) Infrasonic waves and volcanic tremor at Stromboli. *Geophys Res Lett* 23:181–184. <https://doi.org/10.1029/95GL03662>
- Ripepe M, Ciliberto S, Della Schiava M (2001) Time constraints for modeling source dynamics of volcanic explosions at Stromboli. *J Geophys Res* 106:8713–8727. <https://doi.org/10.1029/2000JB900374>
- Ripepe M, Harris AJL, Carniel R (2002) Thermal, seismic and infrasonic evidences of variable degassing rates at Stromboli Volcano. *J Volcanol Geotherm Res* 118:285–297. [https://doi.org/10.1016/S0377-0273\(02\)00298-6](https://doi.org/10.1016/S0377-0273(02)00298-6)
- Ripepe M, Harris AJL, Marchetti E (2005) Coupled thermal oscillations in explosive activity at different craters of Stromboli Volcano. *Geophys Res Lett* 32:L17302. <https://doi.org/10.1029/2005GL022711>
- Ripepe M, Marchetti D, Ulivieri G (2007) Infrasonic monitoring at Stromboli Volcano during the 2003 effusive eruption: insights on the explosive and degassing process of an open conduit system. *J Geophys Res* 112:B09207. <https://doi.org/10.1029/2006JB004613>
- Ripepe M, Delle Donne D, Lacanna G, Marchetti E, Ulivieri G (2009) The onset of the 2007 Stromboli effusive eruption recorded by an integrated geophysical network. *J Volcanol Geotherm Res* 182:131–136. <https://doi.org/10.1016/j.jvolgeores.2009.02.011>

- Ripepe M, Delle Donne D, Genco R, Maggio G, Pistolesi M, Marchetti E, Lacanna G, Ulivieri G, Poggi P (2015) Volcano seismicity and ground deformation unveil the gravity-driven magma discharge dynamics of a volcanic eruption. *Nat Commun* 6:6998. <https://doi.org/10.1038/ncomms7998>
- Rittmann A (1931) Der Ausbruch des Stromboli am 11 September 1930. *Zeits Vulkanol* 14:47–77.
- Rosi M (1980) The island of Stromboli. *Rend Soc Ital Mineral Petrol* 36:345–368.
- Rosi M, Bertagnini A, Landi P (2000) Onset of the persistent activity at Stromboli Volcano (Italy). *Bull Volcanol* 62:294–300. <https://doi.org/10.1007/s004450000098>
- Rosi M, Bertagnini A, Harris AJL, Pioli L, Pistolesi M, Ripepe M (2006) A case history of paroxysmal explosion at Stromboli: timing and dynamics of the April 5, 2003 event. *Earth Planet Sc Lett* 243:594–606. <https://doi.org/10.1016/j.epsl.2006.01.035>
- Rosi M, Pistolesi M, Bertagnini A, Landi P, Pompilio M, Di Roberto A (2013) Stromboli Volcano, Aeolian Islands (Italy): present eruptive activity and hazards. In: Lucchi F, Peccerillo A, Keller J, Tranne CA, Rossi PL (eds) *The Aeolian Islands Volcanoes*. *Geol Soc Lond Mem* 37:473–490. <https://doi.org/10.1144/M37.14>
- Rymer H, van Wyk de Vries B, Stix J, Williams-Jones G (1998) Pit crater structure and processes governing persistent activity at Masaya Volcano, Nicaragua. *Bull Volcanol* 59:345–355. <https://doi.org/10.1007/s004450050196>
- Saad MA (1985) *Compressible Fluid Flow*. Prentice-Hall, Englewood Cliffs, pp 1–560.
- Salvatore V, Silleni A, Corneli D, Taddeucci J, Palladino DM, Sottili G, Bernini D, Andronico A, Cristaldi A (2016) Vent activity and evolution at Stromboli volcano (Aeolian Islands, Italy) between 2005 and 2009. *Rittmann Giovani Ricercatori Conference, Bari, Italy, 13–15 December 2016*. <https://doi.org/10.13140/RG.2.2.25873.02405>
- Salvatore V, Silleni A, Corneli D, Taddeucci J, Palladino DM, Sottili G, Bernini D, Andronico A, Cristaldi A (2018) Parameterizing multi-vent activity at Stromboli Volcano (Aeolian Islands, Italy). *Bull Volcanol* 80:64. <https://doi.org/10.1007/s00445-018-1239-8>
- Scheu B, Spieler O, Dingwell DB (2006) Dynamics of explosive volcanism at Unzen volcano: an experimental contribution. *Bull Volcanol* 69:175–187. <https://doi.org/10.1007/s00445-006-0066-5>
- Schleicher M (1993) Eine einfaches und effizientes Verfahren zur Lösung des Riemann-Problems. *Z Flugwiss Weltraumforsch* 17:265–269.

- Schmid R (1981) Descriptive nomenclature and classification of pyroclastic deposits and fragments: recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks. *Geology* 9:41–43. <https://doi.org/10.1007/BF01822152>
- Settle M, McGetchin TR (1980) Statistical analysis of persistent explosive activity at Stromboli, 1971: implications for eruption prediction. *J Volcanol Geotherm Res* 8:45–58. [https://doi.org/10.1016/0377-0273\(80\)90006-2](https://doi.org/10.1016/0377-0273(80)90006-2)
- Seyfried R (1997) Magmatische Fragmentierung und vulkanische Fontänen: Theoretische Analyse und experimentelle Simulation der strömungsmechanischen Prozesse. PhD thesis GEOMAR Forschungszentrum, Christian-Albrechts-Universität zu Kiel, Kiel, Germany.
- Seyfried R, Hort M (1999) Continuous monitoring of volcanic eruption dynamics: a review of various techniques and new results from a frequency-modulated radar Doppler system. *Bull Volcanol* 60:627–639. <https://doi.org/10.1007/s004450050256>
- Sod GA (1978) A survey of several finite difference methods for systems of nonlinear hyperbolic conservation laws. *J Comput Phys*, 27:1–31. [https://doi.org/10.1016/0021-9991\(78\)90023-2](https://doi.org/10.1016/0021-9991(78)90023-2)
- Sohn YK, Park KH (2005) Composite tuff ring/cone complexes in Jeju Island, Korea: possible consequences of substrate collapse and vent migration. *J Volcanol Geotherm Res* 141:157–175. <https://doi.org/10.1016/j.jvolgeores.2004.10.003>
- Sommerfeld M, Huber N (1999) Experimental analysis and modelling of particle-wall collisions. *Int J Multiphase Flow* 25:1457–1489. [https://doi.org/10.1016/S0301-9322\(99\)00047-6](https://doi.org/10.1016/S0301-9322(99)00047-6)
- Spampinato L, Calvari S, Oppenheimer C, Lodato L (2008) Shallow magma transport for the 2002–03 Mt. Etna eruption inferred from thermal infrared surveys. *J Volcanol Geoth Res* 177:301–312. <https://doi.org/10.1016/j.jvolgeores.2008.05.013>
- Sparks RSJ (1978) The dynamics of bubble formation and growth in magmas: a review and analysis. *J Volcanol Geotherm Res* 3:1–37. [https://doi.org/10.1016/0377-0273\(78\)90002-1](https://doi.org/10.1016/0377-0273(78)90002-1)
- Spieler O, Dingwell DB, Alidibirov M (2004a) Magma fragmentation speed: an experimental determination. *J Volcanol Geotherm Res* 129:109–123. [https://doi.org/10.1016/S0377-0273\(03\)00235-X](https://doi.org/10.1016/S0377-0273(03)00235-X)
- Spieler O, Kennedy B, Kueppers U, Dingwell DB, Scheu B, Taddeucci J (2004b) The fragmentation threshold of pyroclastic rocks. *Earth Planet Sci Lett* 226:139–148. <https://doi.org/10.1016/j.epsl.2004.07.016>

- Stix J, Phillips JC (2012) An analog investigation of magma fragmentation and degassing: effects of pressure, volatile content and decompression rate. *J Volcanol Geotherm Res* 211–212:12–23. <https://doi.org/10.1016/j.jvolgeores.2011.10.001>
- Taddeucci J, Pompilio M, Scarlato P (2002) Monitoring the explosive activity of the July–August 2001 eruption of Mt. Etna (Italy) by ash characterization. *Geophys Res Lett* 29:1029–1032. <https://doi.org/10.1029/2001GL014372>
- Taddeucci J, Scarlato P, Capponi A, Del Bello E, Cimarelli C, Palladino D, Kueppers U (2012a) High-speed imaging of Strombolian explosions: the ejection velocity of pyroclasts. *Geophys Res Lett* 39:L02301. <https://doi.org/10.1029/2011GL050404>
- Taddeucci J, Alatorre-Ibargüengoitia MA, Moroni M, Tornetta L, Capponi A, Scarlato P, Dingwell DB, De Rita D (2012b) Physical parameterization of Strombolian eruptions via experimentally-validated modeling of high-speed observations. *Geophys Res Lett* 39:L16306. <https://doi.org/10.1029/2012GL052772>
- Taddeucci J, Valentine GA, Sonder I, White JDL, Ross P-S, Scarlato P (2013a) The effect of pre-existing craters on the initial development of explosive volcanic eruptions: an experimental investigation. *Geophys Res Lett* 40:507–510. <https://doi.org/10.1002/grl.50176>
- Taddeucci J, Palladino DM, Sottili G, Bernini D, Andronico D, Cristaldi A (2013b) Linked frequency and intensity of persistent volcanic activity at Stromboli (Italy). *Geophys Res Lett* 40:3384–3388. <https://doi.org/10.1002/grl.50652>
- Taddeucci J, Capponi A, Scarlato P, Palladino DM, Cocomello S, Gaudin D (2013c) The slug buster: an analogue experiment for the study of Strombolian explosions. IAVCEI Scientific Assembly 2013, Kagoshima, Japan, 20–24 July 2013. <http://www.kazan.or.jp/iavencei2013/iavenceihp/PDF/0P12K-O7.pdf>
- Taddeucci J, Edmonds M, Houghton B, James MR, Vergnolle S (2015) Hawaiian and Strombolian eruptions. In: Sigurdsson H, Houghton B, Rymer H, Stix J, McNutt S (eds) *The encyclopedia of volcanoes* 2nd edn. Academic Press, Amsterdam, pp 485–503. <https://doi.org/10.1016/B978-0-12-385938-9.00027-4>
- Taddeucci J, Alatorre-Ibargüengoitia MA, Cruz-Vázquez O, Del Bello E, Scarlato P, Ricci T (2017) In-flight dynamics of volcanic ballistic projectiles. *Rev Geophys* 55:675–718. <https://doi.org/10.1002/2017RG000564>
- Taddeucci J, Salvatore V, Cigala V, Gaudin D, Pena-Fernandez JJ, Arciniega-Ceballos A, Kueppers U, Palladino DM, Sesterhenn J (2018) Shock-tube investigation on jet

- development and pyroclast acceleration during transient explosive eruptions. Cities on Volcanoes 10, Naples, Italy, 2–7 September 2018.
- Turcotte DL, Ockendon H, Ockendon JR, Cowley SJ (1990) A mathematical model of vulcanian eruptions. *Geophys J Int* 103:211–217. <https://doi.org/10.1111/j.1365-246X.1990.tb01763.x>
- Vaggelli G, Francalanci L, Ruggieri G, Testi S (2003) Persistent polybaric rests of calc-alkaline magmas at Stromboli Volcano, Italy: pressure data from fluid inclusions in relict quartzite nodules. *Bull Volcanol* 65:385–404. <https://doi.org/10.1007/s00445-002-0264-8>
- Valade S, Lacanna G, Coppola D, Laiolo M, Pistolesi M, Delle Donne D, Genco R, Marchetti E, Ulivieri G, Allocca C, Cigolini C, Nishimura T, Poggi P, Ripepe M (2016) Tracking dynamics of magma migration in open-conduit systems. *Bull Volcanol* 78:78. <https://doi.org/10.1007/s00445-016-1072-x>
- Valentine GA, Gregg TKP (2008) Continental basaltic volcanoes—processes and problems. *J Volcanol Geotherm Res* 177:857–873. <https://doi.org/10.1016/j.jvolgeores.2008.01.050>
- Vergnolle S, Brandeis G (1996) Strombolian explosions. 1. A large bubble breaking at the surface of a lava column as a source of sound. *J Geophys Res* 101:20433–20447. <https://doi.org/10.1029/96JB01178>
- Wadsworth FB, Kennedy BM, Branney MJ, von Aulock FW, Lavallée Y, Menendez A (2015) Exhumed conduit records magma ascent and drain-back during a Strombolian eruption at Tongariro volcano, New Zealand. *Bull Volcanol* 77:71. <https://doi.org/10.1007/s00445-015-0962-7>
- Waite GP, Nadeau PA, Lyons JJ (2013) Variability in eruption style and associated very long period events at Fuego volcano, Guatemala. *J Geophys Res* 118:1526–1533. <https://doi.org/10.1002/jgrb.50075>
- Washington HS (1917) Persistence of vents at Stromboli and its bearing on volcanic bearing. *Geol Soc Am Bull* 28:249–278. <https://doi.org/10.1130/GSAB-28-249>
- Weill A, Brandeis G, Vergnolle S, Baudin F, Bilbille J, Fèvre J-F, Piron B, Hill X (1992) Acoustic sounder measurements of the vertical velocity of volcanic jets at Stromboli volcano. *Geophys Res Lett* 19:2357–2360. <https://doi.org/10.1029/92GL02502>
- White JDL, Valentine GA (2016) Magmatic versus phreatomagmatic fragmentation: absence of evidence is not evidence of absence. *Geosphere* 12:1478–1488. <https://doi.org/10.1130/GES01337.1>

- Wilson L, Sparks RSJ, Walker GPL (1980) Explosive Volcanic Eruptions IV. The control of magma properties and conduit geometry on eruption column behaviour. *Geophys J R Astr Soc* 63: 117–148. <https://doi.org/10.1111/j.1365-246X.1980.tb02613.x>
- Woods AW (1995) A model of Vulcanian explosions. *Nucl Eng Des* 155:345–357. [https://doi.org/10.1016/0029-5493\(94\)00881-X](https://doi.org/10.1016/0029-5493(94)00881-X)
- Woods AW, Bower SM (1995) The decompression of volcanic jets in a crater during explosive volcanic eruptions. *Earth Planet Sc Lett* 131:189–205. [https://doi.org/10.1016/0012-821x\(95\)00012-2](https://doi.org/10.1016/0012-821x(95)00012-2)
- Zanon V, Neri M, Pecora E (2009) Interpretation of data from the monitoring thermal camera of Stromboli Volcano (Aeolian Islands, Italy). *Geol Mag* 146:591–601. <https://doi.org/10.1017/S0016756809005937>
- Zhang G, Setoguchi T, Kim HD (2015) Numerical simulation of flow characteristics in micro shock tubes. *J Therm Sci* 24:246–253. <https://doi.org/10.1007/s11630-015-0780-4>
- Zimanowski B, Büttner R, Lorenz V, Häfele HG (1997) Fragmentation of basaltic melt in the course of explosion volcanism. *J Geophys Res* 102:803–814. <https://doi.org/10.1029/96JB02935>

ACKNOWLEDGEMENTS

Firstly, I would like to thank prof. Danilo Mauro Palladino, the first supervisor of this thesis, for his availability and accuracy shown during the whole my PhD, as well as for the great knowledge that he has given me.

I am also deeply indebted with my co-tutor, dr. Jacopo Taddeucci, for his patience and fruitful scientific discussions during the whole three-year-long work, he taught me a lot.

I thank Aurora, Davide, and Valeria for the work done together and for the hilarious times, without them this work would not have come to life. I would like to thank all colleagues I met either during my field and laboratory activities and during my stay in Munich, in particular Alejandra, Betta, Damien, Daniele, Gianluca, Piergiorgio, Pierre-Yves, Tullio, and Ulli: from each of them I had something to learn, but above all I will remember all the courtesy, availability, and simplicity. I thank Francesco, because he always showed me the other side of coin.

A big thank you to my mother and father, who with their sweet and unflagging support have allowed me to arrive here, contributing to my personal training. I also thank with affection my brother Alessandro and my sisters Agnese and Federica, with whom I shared funny moments that made me forget about all the work that awaited me. Thanks to my grandparents Enzo and Anna for the love they have never made me miss, for always being proud of me. Thanks to Lorenzo, Assunta, Sara, and Antonio, who have become my second family.

I thank a unique and special person, Erika, my love, my best friend, my life. Since we are known, you have supported me day by day, showing you always proud and satisfied with my goals. Especially during these three years, we have overcome always together all the difficulties step by step, celebrating each victory together and raising stronger than before after each failure. Thank you for enduring my stress and craziness during these three years of intense work. Thank you for being by my side, always.

Finally, I would like to thank my friends Angelica, Francesca, Gabriele, Giovanni, Giuliano, and Ilaria. We have always supported each other, in good times and in bad luck, and even if either we are in different cities or we have chosen different routes, I will carry in my heart forever the funny, crazy, and extravagant moments spent together.