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## ► To cite this version:

Guillaume Georgeais, Andrew J. L. Harris, Yves Moussallam, Kenneth T. Koga, Estelle F. Rose-Koga. An empirical relation between velocity, mass discharge rate and vent area for normal through paroxysmal eruptions at Stromboli. *Bulletin of Volcanology*, 2024, 86, 10.1007/s00445-024-01718-8 . insu-04500697

**HAL Id: insu-04500697**

**<https://insu.hal.science/insu-04500697>**

Submitted on 14 Mar 2024

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1 Type of Paper: Short Scientific Communication

2 **An empirical relation between velocity, mass discharge rate and vent area**  
3 **for normal through paroxysmal eruptions at Stromboli**

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16  
17 **Abstract**

18 Based on published and new data for explosive events at Stromboli (Italy), we propose an  
19 empirical relation that links mass discharge rate (MDR) and at-vent gas jet velocity ( $G_v$ ). We  
20 use 65 simultaneous measurements of MDR and  $G_v$  and find two trends in both the cross-  
21 correlation and rank order statistics. Cross-correlation gives a power law relation:  $MDR =$   
22  $10^{(0.015G_v+2.434)}$  kg/s,  $R^2=0.81$ , and applies to ash-dominated emissions. Combining this  
23 relation with the conservation of mass equation allows at-vent plume density and/or vent area  
24 to be derived from  $MDR = G_v \rho A$ ,  $\rho$  being plume density and  $A$  being vent cross-sectional area.  
25 We find that while a vent radius of 2 m and plume density of  $0.35 \text{ kg/m}^3$  fits with the “normal”  
26 activity at Stromboli, a  $290 \times 2.5$  m vent area likely feeds a  $10 \text{ kg/m}^3$  jet during paroxysmal  
27 activity. Initial tests on available data shows promise in extending the correlation beyond  
28 Stromboli and/or to events with higher MDR ( $>10^7$  kg/s). However, the exact relation will  
29 depend on magma composition, temperature and volatile content, as well as conduit radius and  
30 vent overpressure.

31 **Keywords:** Thermal imagery, Eruption intensity, Mass Discharge Rate, Particle Velocity,  
32 Gas Jet Velocity, Stromboli

### 33 **Acknowledgments**

34 GG thanks Lucia Gurioli for her time and discussions about Stromboli volcano. We thank Larry  
35 Mastin and three other reviewers for their detailed and constructive comments and  
36 recommendations and Sara Barsotti for editorial handling.

### 37 **Funding**

38 GG was supported by a PhD fellowship from the French Government “Ministère de  
39 l’Enseignement Supérieur, de la Recherche et de l’Innovation”. GG acknowledges the financial  
40 support from the laboratory of excellence ClerVolc for this project. This is contribution no. 601  
41 of the ClerVolc program of the International Research Center for Disaster Sciences and  
42 Sustainable Development of the University of Clermont Auvergne.

### 43 **Conflicts of interest/Competing interests**

44 The authors declare no conflicts nor competing interest

### 45 **Introduction**

46 Mass Discharge Rate (MDR, kg/s) is commonly used to classify the “explosiveness” of a  
47 volcanic eruption, especially through the Volcanic Explosivity Index (Newhall and Self, 1982).  
48 Time-averaged MDR can be estimated from the total erupted mass divided by eruption duration  
49 (e.g., Mason et al. 2004; Bryan et al. 2010; Pyle, 2015). Peak MDR has also been derived from  
50 maximum plume height, as MDR is proportional to plume height to the power-of-four for  
51 Vulcanian-to-Plinian eruptions (Wilson et al. 1978). Geophysical signals, such as seismicity,  
52 infrasound and Doppler radar (e.g., Brodsky et al. 1999; Freret-Lorgeril et al. 2018; Perttu et  
53 al., 2020; Maki et al. 2021), as well as lightning intensity rates (Van Eaton et al., 2016), have  
54 also been tested as a proxy for MDR.

55 We propose a further option for deriving MDR from thermal or visible video using an  
56 empirical relation between MDR and gas jet velocity ( $G_v$ ). We initially explore this relation for  
57 explosive events at Stromboli (Italy) where there is excellent constraint on the plumbing system  
58 (e.g., Bertagnini et al. 1999, 2013; Métrich et al. 2005, 2010, 2021), explosion source  
59 mechanisms (e.g., Chouet et al. 1999; Ripepe and Gordeev 1999; Ripepe et al. 2001) and  
60 emission dynamics (e.g., Patrick et al. 2007; Scharff et al. 2008; Gurioli et al. 2013). As a result  
61 data are available to test a relation between MDR and  $G_v$ . Stromboli also displays a range of  
62 explosive activity, which are commonly separated into three groups (Barberi et al. 1993). These  
63 are, in order of increasing magnitude: normal, major and paroxysmal. Named by Barberi et al.  
64 (1993) to describe the typical explosive activity that occurs at Stromboli, “normal” eruptions  
65 send  $10\text{--}10^4$  kg of bombs, gas and ash to a height of a few 10s to a few 100 m typically  $\sim 10$   
66 times an hour (Harris and Ripepe 2007; Patrick et al. 2007; Harris et al. 2013). Major eruptions  
67 can occur several times a year, involve  $10^5\text{--}10^7$  kg of bombs and ash, and send plumes to around  
68 a kilometre in height (Gurioli et al. 2013). Paroxysms are rarer, with four having occurred  
69 between 2003 and 2019, and form buoyant ash-rich plumes that ascend to several kilometres,  
70 and involve  $>10^8$  kg (Rosi et al., 2006; Pistolesi et al. 2011; Giordano and De Astis 2020).  
71 The wealth of data for explosions at Stromboli makes it an ideal location to test relations  
72 between a variety of eruption source terms (e.g., MDR and vent area) and plume ascent  
73 parameters (e.g., emission velocity and plume ascent velocity). We thus use Stromboli to  
74 explore an empirical relation between at-vent gas velocity and MDR using published and new  
75 datasets for which the two parameters can be simultaneously derived.

## 76 **Method**

77 We examined 65 eruptive events (59 normal, two major and four paroxysmal) for which  
78 suitable data were available (Table 1). Harris et al. (2013) obtained the mass ( $m$ ) of 21 normal  
79 eruptions from thermal video using the amount of energy lost by the bomb field during cooling.

80 However, the duration ( $t$ ) for these events was not assessed, so we revisited the data to obtain  
81 emission duration so that time-averaged MDR could be obtained from  $m/t$ . Duration was taken  
82 as the time between the first appearance of the plume and the last bomb to exit the vent. Videos  
83 used were recorded at 30 frames per second, and in the compressed data 10 frames were  
84 equivalent to one second of recording. The uncertainty is five frames (0.5 s), so that  
85 (considering the same uncertainty for the start and end of the event) error on duration is  $\pm 1$  s.

86 We also used the mass, particle ejection velocity and duration 31 eruptions as obtained by  
87 Bombrun et al. (2015) through particle tracking to convert to time-averaged MDR. In addition,  
88 we included MDR and gas ejection velocities for transient ash-dominated normal eruptions at  
89 Stromboli as derived from thermal and visible imagery by Tournigand et al. (2017).

90 Mass discharge rates for major and paroxysmal eruptions at Stromboli were taken from the  
91 literature as follows:

- 92 • For the 8 and 24 November 2009 major eruptions MDR was taken from Gurioli et al.  
93 (2013);
- 94 • For the 2003 and 2007 paroxysms, we used the MDR of Rosi et al. (2006) and Pistolesi  
95 et al. (2011), respectively;
- 96 • MDR for the July and August 2019 paroxysms were calculated from maximum plume  
97 height by Giordano and De Astis (2020) following the equation of Mastin et al. (2009).

98 A theoretical relation between ballistic exit velocity ( $Bv$ ) and gas exit velocity ( $Gv$ ) was  
99 proposed by Steinberg and Babenko (1978). In this relation,  $Gv$  represents the speed of the gas  
100 to which the finest particles are coupled, and  $Bv$  represents the velocity of particles large enough  
101 to be affected by drag, as tested on and applied to normal eruptions at Stromboli by Ripepe et  
102 al. (1993) and Harris et al. (2012b).

103 Ballistic velocities are obtained either through particle tracking and given by Harris et al.  
104 (2013) and Bombrun et al. (2015) for normal explosions, or ballistic trajectory modeling for  
105 major (Gurioli, Colo, et al., 2013; Pioli et al., 2014) and paroxysmal events (Rosi et al., 2006;  
106 Pistolesi et al., 2011; Andronico et al., 2013; Giordano & De Astis, 2020). We convert these  
107 ballistic velocities ( $B_v$ ) to gas jet velocities ( $G_v^b$ ) using equation (8) of Harris et al. (2012b):

$$108 \quad G_v^b = 1.41 \times B_v + 15.3 \quad (1)$$

109 This relation is set for explosions at Stromboli and correlates well with directly measured gas  
110 ejection velocities (Fig. 1). The literature-derived database is given in Table 1, and our  
111 calculated MDR data are given in Table 2.

## 112 **Results**

113 The 21 normal explosions at Stromboli recorded by Harris et al. (2013) lasted between 3 and  
114 28 seconds, giving MDRs ranging from 32 to 800 kg/s (Table 2). Eruptions from vent NE1  
115 lasted longer (average of 18 s) than eruptions from NE2 (average of 6 s). This leads to a wider  
116 range of MDR values for events at NE2 than NE1 (Fig. 2a). In Figure 2a, data from Bombrun  
117 et al. (2015) fall in a cluster of low MDR and high gas velocities (150–250 m/s,  $\text{MDR} < 10^4$   
118 kg/s), and data from Tournigand et al. (2017) have high MDR with low gas velocities ( $< 150$   
119 m/s,  $\text{MDR} \geq 10^4$  kg/s). MDR for these normal explosions show correlations with gas velocity  
120 with an  $R^2$  of between 0.5 and 0.83 depending on the data set used (Fig. 2a).

121 MDR for the major and paroxysmal events range between  $10^4$  and  $10^7$  kg/s, with gas jet  
122 velocities in the range 142–297 m/s (Table 1). The relation between MDR and gas velocity for  
123 the six major and paroxysmal explosions shows a positive, linear correlation with an  $R^2$  of 0.79.  
124 Eruption magnitudes have a power-law dependence (Pyle, 1998). This can be expressed as a  
125 rank order plot, as obtained by sorting the values from the highest to the lowest (Sornette et al.  
126 1996). This method can be used to constrain whether the dataset is homogeneous (cf. Schneider

127 and Barbera, 1998) within a single volcanic system. The rank order plot for our Stromboli data  
128 shows two trends representing two different populations (Fig. 3). These two populations are  
129 apparent in the rank order statistics for both gas velocity and MDR and involve a first group of  
130 low gas velocity and MDR, and a second group of high gas velocity and MDR. We thus define  
131 two main populations and treat them separately. The first involves ballistic-dominated normal  
132 emissions (Fig. 2a). The second includes all major and paroxysmal events, plus one ash-  
133 dominated normal eruption, this population being of ash-rich emissions involving plume ascent  
134 dominated by buoyancy (Fig. 2b)

## 135 **Discussion**

136 The two trends apparent for Stromboli in the cross-correlation (Fig. 2) and rank order (Fig. 3)  
137 plots result from the different plume types considered and differences in their associated ascent  
138 dynamics. Normal explosions at Stromboli are associated with slug flow in the conduit  
139 (Gonnermann and Manga, 2012) and are characterized by very low levels of fragmentation to  
140 produce bomb-dominated plumes with particles that follow ballistic trajectories (e.g., Chouet  
141 et al. 1974; Patrick et al. 2007; Gurioli et al. 2013). In contrast, major and paroxysmal events  
142 involve rapid ascent of magma coupled with a gas phase ascending from depths of 7–10 km  
143 and are characterized by higher degrees of fragmentation (e.g., Bertagnini et al. 1999; Métrich  
144 et al. 2005, 2010, 2021; Pioli et al. 2014). The result is an ash-dominated plume whose ascent  
145 is characterized by a longer steady convection-dominated phase (cf. Wilson and Self 1980; Rosi  
146 et al. 2006; Harris et al. 2008).

147 Cross-correlation using data for ballistic-dominated normal explosions at Stromboli gives a  
148 relation between MDR and  $G_v$  of (Fig. 2a, yellow regression line):

$$149 \quad MDR = 10^{(0.003G_v+1.933)} \quad R^2 = 0.50 \quad (2a)$$

150 Considering only a single vent improves the correlation, where the relation for vent NE1 (Fig.  
151 2a, blue regression line) is:

152 
$$MDR = 10^{(0.004G_v+1.906)} \quad R^2 = 0.83 \quad (2b)$$

153 These two relations are consistent with differences in vent size, gas/particle ratio, crater  
154 geometry, overpressure and volatile content between craters and events.

155 Finally, the cross-correlation for ash-dominated normal, major and paroxysmal events gives

156 
$$MDR = 10^{(0.015G_v+2.434)} \quad R^2 = 0.81 \quad (3)$$

157 This is the black regression line of Figure 2b.

### 158 **The next largest event at Stromboli?**

159 Application of maximum likelihood statistics to our rank order plots (cf. Sornette et al. 1996;  
160 Pyle 1998) can indicate the most probable MDR and gas velocity for the hypothetical, but next  
161 largest, eruption not recorded in our data (i.e., an event larger than the 2003 paroxysm). On this  
162 basis an eruption at Stromboli larger than the 2003 paroxysm would have an MDR of  $2.19 \times$   
163  $10^7$  kg/s and a gas ejection velocity of 338 m/s. Our current data set for Stromboli is missing at  
164 least two paroxysms, i.e., those of 1456 and 1930. Both have been described as being larger  
165 than the 2003 paroxysm (e.g., Rosi et al. 2006; Bertagnini et al. 2011; Métrich et al. 2021), but  
166 both lack an assessment of MDR and  $G_v$ . We thus speculate that the MDR and  $G_v$  calculated  
167 for the next largest eruption in our dataset are possibly representative of the 1456 and 1930  
168 paroxysms.

### 169 **Vent size during normal and paroxysmal activity**

170 MDR is related to bulk average ( $V$ ) velocity, gas-particle mixture density ( $\rho$ ) and vent cross  
171 sectional area,  $A$ :

172 
$$MDR \approx \rho VA \quad (4)$$

173 Given a vent radius typical for Stromboli, i.e., 2 m (Harris et al. 2012b), we use our range of  
174 ejection velocities and MDR values to solve for mixture density. We find that the normal gas  
175 and ballistic-dominated events fit with a cloud density of  $0.35 \text{ kg/m}^3$  (Fig. 2a). This corresponds



176 to the density of water vapor at 650 K. Instead, ash-dominated normal events fit with  $10 \text{ kg/m}^3$   
177 (Fig. 2a). Note, that these values are for at-vent conditions and are hence in the gas-thrust region  
178 of the jet before entrainment of air.

179 The lower and higher limits of the data set for major and paroxysmal eruptions can only be  
180 reproduced with a cloud density of 10 and  $2600 \text{ kg/m}^3$ , respectively (Fig. 2b). The latter density  
181 is close to the dense-rock value of basaltic magma, and does not provide a realistic plume  
182 density. For paroxysmal eruptions the conduit radius likely exceeds 2 m. Using the MDR and  
183  $G_v$  for the July 2019 paroxysm (Table 1), with a cloud density of  $10 \text{ kg/m}^3$ , gives a circular vent  
184 radius of  $\sim 13$  m. A 290 m long and 2.5 m wide source also provides a fit for the paroxysmal  
185 events. This would represent an eruption from the entire length of a SW-NE trending dyke  
186 underlying the crater terrace, and is consistent with emission from all three active craters during  
187 a paroxysm (Rosi et al., 2006). It is also consistent with collapse of the crater terrace following  
188 paroxysms to create a continuous trench in place of the typical three-crater system that  
189 characterizes Stromboli's crater terrace during normal activity (cf. Harris and Ripepe, 2007)  
190 and the ejection of meter-sized blocks of the "shattered shallow subvolcanic system" (Renzulli  
191 et al., 2009).

192 We calculate the at-vent volume fraction of pyroclasts ( $f$ ) within the plume using a simple  
193 mixture model:

$$194 \quad \rho \approx f \times \rho_{pyroclast} + (1 - f) \times \rho_{gas} \quad (5)$$

195 An average pyroclast density ( $\rho_{pyroclast}$ ) of  $\sim 800 \text{ kg/m}^3$  (Pichavant et al. 2022), a gas density  
196 ( $\rho_{gas}$ ) of  $0.35 \text{ kg/m}^3$  (Harris et al. 2013), and a plume density of  $10 \text{ kg/m}^3$  results in a mixture  
197 of  $\sim 1$  % pyroclasts and  $\sim 99$  % gas volumes (respectively  $\sim 97$  % pyroclasts and  $\sim 3$  % gas mass  
198 fraction). A low gas weight fraction indicates that the cloud was ejected out of the vent without  
199 any mixing with the atmosphere (Wilson and Self, 1980).

200 **Towards a global predictive model for eruption intensity?**

201 At-vent gas and particle velocities vary as a function of vent geometry, over-pressure, magma  
202 temperature, volatile content, particle size and gas density (Steinberg and Babenko, 1978;  
203 Woods and Bower, 1995). By restricting our consideration to a single system, we limit the  
204 variation in volatile content, temperature, crater/vent geometry, pressure, ash/gas ratio, and gas  
205 density. Our results for Stromboli indicate that, if eruption types and styles are considered  
206 separately according to their dynamics, and measurements of mass eruption rate, gas velocity  
207 and particle velocity are available, then an empirical relation relating the three can be derived.  
208 We assess whether this can be extended to other, higher magnitude systems by considering:

- 209 • Pinatubo 1991 (VEI = 6; based on the data from Simkin et al, 1981);
- 210 • Mt. St. Helens 1980 (VEI = 5; Venzke 2022);
- 211 • Fuego 2012 (VEI ≤ 2; Venzke 2022);
- 212 • Sakurajima 2013 (VEI ≤ 3; Venzke 2022).

213 For Fuego and Sakurajima we take the MDR and  $G_v$  as derived from thermal and visible  
214 imagery by Tournigand et al. (2017). For Pinatubo, an MDR ranging between  $6.8 \times 10^8$  and  $10^9$   
215 kg/s has been calculated from granulometry (Koyaguchi and Ohno 2001) and satellite data  
216 (Koyaguchi and Tokuno 1993). MDR estimates for Mt. St. Helens range from an average of 2  
217  $\times 10^7$  kg/s for the whole eruption (Carey and Sigurdsson, 1985; Pyle, 2015), to  $2\text{--}6 \times 10^9$  kg/s  
218 for the initial lateral blast (Brodsky et al. 1999). In all cases, we use the full range. For Pinatubo  
219 whether we calculate gas velocity using the at-vent decompressing jet model (6) or the freely  
220 decompressing model (7) of Woods and Bower (1995) is debatable:

$$221 \quad G_v = 0.95 \times (n_0 RT)^{1/2} \quad (6)$$

$$222 \quad G_v = 1.85 \times (n_0 RT)^{1/2} \quad (7)$$

223 Here  $n_0$  is the difference between melt inclusion volatile concentration (6.4–7 wt %, Rutherford  
224 and Devine, 1996) and glass matrix average volatile concentration (1.45 wt.%, Hammer et al.,  
225 1999),  $R$  is the vapor-gas constant (461.5 J/kg K), and  $T$  is the magma temperature (1073 K).  
226 The value we obtain is likely a maximum since experimental studies suggested disequilibrium  
227 degassing for this eruption (Mangan and Sisson, 2000), which would delay nucleation and thus  
228 decrease magma ascent rate and  $G_v$ . For Mt. St. Helens we use the range of velocities for the  
229 Plinian phase given by Carey and Sigurdsson (1985) and Woods and Bower (1995), i.e., 200–  
230 300 m/s. We use velocities as close as possible to the vent-leaving values, where the at-surface  
231 decompression of the volcanic jet has the least impact (Woods and Bower, 1995) and where  
232 vent-leaving values can be compared between cases.

233 MDR values for Sakurajima, Pinatubo, and Mt. St. Helens are one-to-three orders of magnitude  
234 higher than those for Stromboli and Fuego at similar  $G_v$  (Fig. 4). However, the relationship  
235 between  $G_v$  and MDR remains linear and positive. This is consistent with the decompressing  
236 jet model of Woods and Bower (1995) for the emission dynamics of gas-particle mixtures,  
237 where variations in magma volatile content, over-pressure, vent geometry, and magma  
238 temperature account for the differences observed between each system (Fig. 4).

## 239 **Conclusion**

240 We derive an empirical relationship between gas jet velocity and MDR which applies to  
241 explosive events at Stromboli with VEI ranging from 0 to 3. At Stromboli, a network of  
242 continuously recording thermal cameras allows measurement of gas jet velocity (Delle Donne  
243 and Ripepe, 2012). This means that real-time measurements of  $G_v$  can potentially be converted  
244 to MDR for the two event types (ballistic and convective emissions) common at this well-  
245 monitored site.

246 Extending the analysis to events with higher VEI suggest a wider applicability a linear relation  
247 between  $G_v$  and MDR. Our argument is thus for a database with simultaneous measurements

248 of MDR and at-vent velocities for a variety of systems, allowing extension of this analysis.  
249 Such data requires a video camera network targeting the vent, which is rarely possible. All the  
250 same, given the importance of MDR as a key source term in forward modeling (cf. Bonadonna  
251 et al. 2011), such a fast and straightforward empirical approach to potentially derive MDR in  
252 near-real time shows promise.

253 **References**

- 254 Andronico, D., Taddeucci, J., Cristaldi, A., Miraglia, L., Scarlato, P., & Gaeta, M. (2013). The 15  
255 March 2007 paroxysm of Stromboli: video-image analysis, and textural and compositional  
256 features of the erupted deposit. *Bulletin of Volcanology*, 75(7), 733.  
257 <https://doi.org/10.1007/s00445-013-0733-2>
- 258 Bertagnini, A., Coltelli, M., Landi, P., Pompilio, M., & Rosi, M. (1999). Violent explosions yield new  
259 insights into dynamics of Stromboli volcano. *Eos, Transactions American Geophysical Union*,  
260 80(52), 633–636. <https://doi.org/10.1029/99EO00415>
- 261 Bertagnini, Antonella, Di Roberto, A., & Pompilio, M. (2011). Paroxysmal activity at Stromboli:  
262 lessons from the past. *Bulletin of Volcanology*, 73(9), 1229–1243.  
263 <https://doi.org/10.1007/s00445-011-0470-3>
- 264 Bertagnini, Antonella, Métrich, N., Francalanci, L., Landi, P., Tommasini, S., & Conticelli, S. (2013).  
265 Volcanology and Magma Geochemistry of the Present-Day Activity: Constraints on the  
266 Feeding System. In S. Calvari, S. Inguaggiato, G. Puglisi, M. Ripepe, & M. Rosi (Eds.),  
267 *Geophysical Monograph Series* (pp. 19–37). Washington, D. C.: American Geophysical  
268 Union. <https://doi.org/10.1029/182GM04>
- 269 Bevilacqua, A., Bertagnini, A., Pompilio, M., Landi, P., Del Carlo, P., Di Roberto, A., et al. (2020).  
270 Major explosions and paroxysms at Stromboli (Italy): a new historical catalog and temporal  
271 models of occurrence with uncertainty quantification. *Scientific Reports*, 10(1), 17357.  
272 <https://doi.org/10.1038/s41598-020-74301-8>
- 273 Bombrun, M., Harris, A., Gurioli, L., Battaglia, J., & Barra, V. (2015). Anatomy of a Strombolian  
274 eruption: Inferences from particle data recorded with thermal video. *Journal of Geophysical*  
275 *Research: Solid Earth*, 120(4), 2367–2387. <https://doi.org/10.1002/2014JB011556>
- 276 Bonadonna, C., Genco, R., Gouhier, M., Pistolesi, M., Cioni, R., Alfano, F., et al. (2011). Tephra  
277 sedimentation during the 2010 Eyjafjallajökull eruption (Iceland) from deposit, radar, and  
278 satellite observations. *Journal of Geophysical Research: Solid Earth*, 116(B12).  
279 <https://doi.org/10.1029/2011JB008462>

- 280 Brodsky, E. E., Kanamori, H., & Sturtevant, B. (1999). A seismically constrained mass discharge rate  
281 for the initiation of the May 18, 1980 Mount St. Helens eruption. *Journal of Geophysical*  
282 *Research: Solid Earth*, 104(B12), 29387–29400. <https://doi.org/10.1029/1999JB900308>
- 283 Bryan, S. E., Peate, I. U., Peate, D. W., Self, S., Jerram, D. A., Mawby, M. R., et al. (2010). The  
284 largest volcanic eruptions on Earth. *Earth-Science Reviews*, 102(3–4), 207–229.  
285 <https://doi.org/10.1016/j.earscirev.2010.07.001>
- 286 Carey, S., & Sigurdsson, H. (1985). The May 18, 1980 eruption of Mount St. Helens: 2. Modeling of  
287 dynamics of the Plinian Phase. *Journal of Geophysical Research: Solid Earth*, 90(B4), 2948–  
288 2958. <https://doi.org/10.1029/JB090iB04p02948>
- 289 Chouet, B., Hamisevicz, N., & McGetchin, T. R. (1974). Photoballistics of volcanic jet activity at  
290 Stromboli, Italy. *Journal of Geophysical Research (1896-1977)*, 79(32), 4961–4976.  
291 <https://doi.org/10.1029/JB079i032p04961>
- 292 Chouet, B., Saccorotti, G., Dawson, P., Martini, M., Scarpa, R., De Luca, G., et al. (1999). Broadband  
293 measurements of the sources of explosions at Stromboli Volcano, Italy. *Geophysical Research*  
294 *Letters*, 26(13), 1937–1940. <https://doi.org/10.1029/1999GL900400>
- 295 Delle Donne, D., & Ripepe, M. (2012). High-frame rate thermal imagery of Strombolian explosions:  
296 Implications for explosive and infrasonic source dynamics. *Journal of Geophysical Research:*  
297 *Solid Earth*, 117(B9). <https://doi.org/10.1029/2011JB008987>
- 298 Freret-Lorgeril, V., Donnadieu, F., Scollo, S., Provost, A., Fréville, P., Guéhenneux, Y., et al. (2018).  
299 Mass Eruption Rates of Tephra Plumes During the 2011–2015 Lava Fountain Paroxysms at  
300 Mt. Etna From Doppler Radar Retrievals. *Frontiers in Earth Science*, 6, 73.  
301 <https://doi.org/10.3389/feart.2018.00073>
- 302 Giordano, G., & De Astis, G. (2020). The summer 2019 basaltic Vulcanian eruptions (paroxysms) of  
303 Stromboli. *Bulletin of Volcanology*, 83(1), 1. <https://doi.org/10.1007/s00445-020-01423-2>
- 304 Global Volcanism Program, & Venzke, E. (2022). *Volcanoes of the World*, v.5 [Data set]. Global  
305 Volcanism Program.
- 306 Gonnermann, H., & Manga, M. (2012). Dynamics of magma ascent in the volcanic conduit Chapter 4  
307 Overview. <https://doi.org/10.1017/cbo9781139021562.004>

- 308 Gurioli, L., Harris, A. J. L., Colò, L., Bernard, J., Favalli, M., Ripepe, M., & Andronico, D. (2013).  
309 Classification, landing distribution, and associated flight parameters for a bomb field  
310 emplaced during a single major explosion at Stromboli, Italy. *Geology*, *41*(5), 559–562.  
311 <https://doi.org/10.1130/G33967.1>
- 312 Gurioli, L., Colo, L., Bollasina, A. J., Harris, A. J. L., Whittington, A., & Ripepe, M. (2013).  
313 Dynamics of Strombolian explosions: Inferences from field and laboratory studies of erupted  
314 bombs from Stromboli volcano. *Journal of Geophysical Research*, *27*.
- 315 Hammer, J. E., Cashman, K. V., Hoblitt, R. P., & Newman, S. (1999). Degassing and microlite  
316 crystallization during pre-climactic events of the 1991 eruption of Mt. Pinatubo, Philippines.  
317 *Bulletin of Volcanology*, *60*(5), 355–380. <https://doi.org/10.1007/s004450050238>
- 318 Harris, A., & Ripepe, M. (2007). Synergy of multiple geophysical approaches to unravel explosive  
319 eruption conduit and source dynamics – A case study from Stromboli. *Geochemistry*, *67*(1),  
320 1–35. <https://doi.org/10.1016/j.chemer.2007.01.003>
- 321 Harris, A.J.L., Delle Donne, D., Dehn, J., Ripepe, M., & Worden, A. K. (2013). Volcanic plume and  
322 bomb field masses from thermal infrared camera imagery. *Earth and Planetary Science*  
323 *Letters*, *365*, 77–85. <https://doi.org/10.1016/j.epsl.2013.01.004>
- 324 Harris, Andrew J. L., Ripepe, M., Calvari, S., Lodato, L., & Spampinato, L. (2013). The 5 April 2003  
325 Explosion of Stromboli: Timing of Eruption Dynamics Using Thermal Data. In S. Calvari, S.  
326 Inguaggiato, G. Puglisi, M. Ripepe, & M. Rosi (Eds.), *Geophysical Monograph Series* (pp.  
327 305–316). Washington, D. C.: American Geophysical Union.  
328 <https://doi.org/10.1029/182GM25>
- 329 Harris, Andrew J.L., Ripepe, M., & Hughes, E. A. (2012). Detailed analysis of particle launch  
330 velocities, size distributions and gas densities during normal explosions at Stromboli. *Journal*  
331 *of Volcanology and Geothermal Research*, *231–232*, 109–131.  
332 <https://doi.org/10.1016/j.jvolgeores.2012.02.012>
- 333 Koyaguchi, T., & Ohno, M. (2001). Reconstruction of eruption column dynamics on the basis of grain  
334 size of tephra fall deposits: 2. Application to the Pinatubo 1991 eruption. *Journal of*

- 335            *Geophysical Research: Solid Earth*, 106(B4), 6513–6533.  
336            <https://doi.org/10.1029/2000JB900427>
- 337 Koyaguchi, T., & Tokuno, M. (1993). Origin of the giant eruption cloud of Pinatubo, June 15, 1991.  
338            *Journal of Volcanology and Geothermal Research*, 55(1), 85–96.  
339            [https://doi.org/10.1016/0377-0273\(93\)90091-5](https://doi.org/10.1016/0377-0273(93)90091-5)
- 340 Leduc, L., Gurioli, L., Harris, A., Colò, L., & Rose-Koga, E. F. (2015a). Types and mechanisms of  
341            strombolian explosions: characterization of a gas-dominated explosion at Stromboli. *Bulletin*  
342            *of Volcanology*, 77(1), 8. <https://doi.org/10.1007/s00445-014-0888-5>
- 343 Leduc, L., Gurioli, L., Harris, A., Colò, L., & Rose-Koga, E. F. (2015b). Types and mechanisms of  
344            strombolian explosions: characterization of a gas-dominated explosion at Stromboli. *Bulletin*  
345            *of Volcanology*, 77(1), 8. <https://doi.org/10.1007/s00445-014-0888-5>
- 346 Maki, M., Kim, Y., Kobori, T., Hirano, K., Lee, D.-I., & Iguchi, M. (2021). Analyses of three-  
347            dimensional weather radar data from volcanic eruption clouds. *Journal of Volcanology and*  
348            *Geothermal Research*, 412, 107178. <https://doi.org/10.1016/j.jvolgeores.2021.107178>
- 349 Mangan, M., & Sisson, T. (2000). Delayed, disequilibrium degassing in rhyolite magma:  
350            decompression experiments and implications for explosive volcanism. *Earth and Planetary*  
351            *Science Letters*, 183(3), 441–455. [https://doi.org/10.1016/S0012-821X\(00\)00299-5](https://doi.org/10.1016/S0012-821X(00)00299-5)
- 352 Mason, B. G., Pyle, D. M., & Oppenheimer, C. (2004). The size and frequency of the largest explosive  
353            eruptions on Earth. *Bulletin of Volcanology*, 66(8), 735–748. [https://doi.org/10.1007/s00445-](https://doi.org/10.1007/s00445-004-0355-9)  
354            [004-0355-9](https://doi.org/10.1007/s00445-004-0355-9)
- 355 Mastin, L. G., Guffanti, M., Servranckx, R., Webley, P., Barsotti, S., Dean, K., et al. (2009). A  
356            multidisciplinary effort to assign realistic source parameters to models of volcanic ash-cloud  
357            transport and dispersion during eruptions. *Journal of Volcanology and Geothermal Research*,  
358            186(1), 10–21. <https://doi.org/10.1016/j.jvolgeores.2009.01.008>
- 359 Métrich, N, Bertagnini, A., & Di Muro, A. (2010). Conditions of Magma Storage, Degassing and  
360            Ascent at Stromboli: New Insights into the Volcano Plumbing System with Inferences on the  
361            Eruptive Dynamics. *Journal of Petrology*, 51(3), 603–626.  
362            <https://doi.org/10.1093/petrology/egp083>



- 363 Métrich, Nicole, Bertagnini, A., Landi, P., Rosi, M., & Belhadj, O. (2005). Triggering mechanism at  
364 the origin of paroxysms at Stromboli (Aeolian Archipelago, Italy): The 5 April 2003 eruption.  
365 *Geophysical Research Letters*, 32(10). <https://doi.org/10.1029/2004GL022257>
- 366 Métrich, Nicole, Bertagnini, A., & Pistolesi, M. (2021a). Paroxysms at Stromboli Volcano (Italy):  
367 Source, Genesis and Dynamics. *Frontiers in Earth Science*, 9.  
368 <https://doi.org/10.3389/feart.2021.593339>
- 369 Métrich, Nicole, Bertagnini, A., & Pistolesi, M. (2021b). Paroxysms at Stromboli Volcano (Italy):  
370 Source, Genesis and Dynamics. *Frontiers in Earth Science*, 9. Retrieved from  
371 <https://www.frontiersin.org/articles/10.3389/feart.2021.593339>
- 372 Newhall, C. G., & Self, S. (1982). The volcanic explosivity index (VEI) an estimate of explosive  
373 magnitude for historical volcanism. *Journal of Geophysical Research*, 87(C2), 1231.  
374 <https://doi.org/10.1029/JC087iC02p01231>
- 375 Patrick, M. R., Harris, A. J. L., Ripepe, M., Dehn, J., Rothery, D. A., & Calvari, S. (2007).  
376 Strombolian explosive styles and source conditions: insights from thermal (FLIR) video.  
377 *Bulletin of Volcanology*, 69(7), 769–784. <https://doi.org/10.1007/s00445-006-0107-0>
- 378 Pichavant, M., Di Carlo, I., Pompilio, M., & Le Gall, N. (2022). Timescales and mechanisms of  
379 paroxysm initiation at Stromboli volcano, Aeolian Islands, Italy. *Bulletin of Volcanology*,  
380 84(4), 36. <https://doi.org/10.1007/s00445-022-01545-9>
- 381 Pioli, L., Pistolesi, M., & Rosi, M. (2014). Transient explosions at open-vent volcanoes: The case of  
382 Stromboli (Italy). *Geology*, 42(10), 863–866. <https://doi.org/10.1130/G35844.1>
- 383 Pistolesi, M., Delle Donne, D., Pioli, L., Rosi, M., & Ripepe, M. (2011). The 15 March 2007 explosive  
384 crisis at Stromboli volcano, Italy: Assessing physical parameters through a multidisciplinary  
385 approach. *Journal of Geophysical Research*, 116(B12), B12206.  
386 <https://doi.org/10.1029/2011JB008527>
- 387 Pyle, D. M. (1998). Forecasting sizes and repose times of future extreme volcanic events. *Geology*,  
388 26(4), 367–370. [https://doi.org/10.1130/0091-7613\(1998\)026<0367:FSARTO>2.3.CO;2](https://doi.org/10.1130/0091-7613(1998)026<0367:FSARTO>2.3.CO;2)
- 389 Pyle, D. M. (2015). Sizes of Volcanic Eruptions. In *The Encyclopedia of Volcanoes* (pp. 257–264).  
390 Elsevier. <https://doi.org/10.1016/B978-0-12-385938-9.00013-4>

- 391 Renzulli, A., Del Moro, S., Menna, M., Landi, P., & Piermattei, M. (2009). Transient processes in  
392 Stromboli's shallow basaltic system inferred from dolerite and magmatic breccia blocks  
393 erupted during the 5 April 2003 paroxysm. *Bulletin of Volcanology*, 71(7), 795–813.  
394 <https://doi.org/10.1007/s00445-009-0265-y>
- 395 Ripepe, M., Rossi, M., & Saccorotti, G. (1993). Image processing of explosive activity at Stromboli.  
396 *Journal of Volcanology and Geothermal Research*, 54(3), 335–351.  
397 [https://doi.org/10.1016/0377-0273\(93\)90071-X](https://doi.org/10.1016/0377-0273(93)90071-X)
- 398 Ripepe, Maurizio, & Gordeev, E. (1999). Gas bubble dynamics model for shallow volcanic tremor at  
399 Stromboli. *Journal of Geophysical Research: Solid Earth*, 104(B5), 10639–10654.  
400 <https://doi.org/10.1029/98JB02734>
- 401 Ripepe, Maurizio, Ciliberto, S., & Della Schiava, M. (2001). Time constraints for modeling source  
402 dynamics of volcanic explosions at Stromboli. *Journal of Geophysical Research: Solid Earth*,  
403 106(B5), 8713–8727. <https://doi.org/10.1029/2000JB900374>
- 404 Rosi, M., Bertagnini, A., Harris, A. J. L., Pioli, L., Pistolesi, M., & Ripepe, M. (2006). A case history  
405 of paroxysmal explosion at Stromboli: Timing and dynamics of the April 5, 2003 event. *Earth  
406 and Planetary Science Letters*, 243(3), 594–606. <https://doi.org/10.1016/j.epsl.2006.01.035>
- 407 Rutherford, M. J., & Devine, J. D. (1996). Preeruption Pressure-Temperature Conditions and Volatiles  
408 in the 1991 Dacitic Magma of Mount Pinatubo. Retrieved October 27, 2022, from  
409 <https://pubs.usgs.gov/pinatubo/ruth/>
- 410 Scharff, L., Hort, M., Harris, A. J. L., Ripepe, M., Lees, J. M., & Seyfried, R. (2008). Eruption  
411 dynamics of the SW crater of Stromboli volcano, Italy — An interdisciplinary approach.  
412 *Journal of Volcanology and Geothermal Research*, 176(4), 565–570.  
413 <https://doi.org/10.1016/j.jvolgeores.2008.05.008>
- 414 Schneider, H., & Barbera, F. (1998). 18 Application of order statistics to sampling plans for inspection  
415 by variables. In *Handbook of Statistics* (Vol. 17, pp. 497–511). Elsevier.  
416 [https://doi.org/10.1016/S0169-7161\(98\)17020-7](https://doi.org/10.1016/S0169-7161(98)17020-7)

- 417 Sornette, D., Knopoff, L., Kagan, Y. Y., & Vanneste, C. (1996). Rank-ordering statistics of extreme  
418 events: Application to the distribution of large earthquakes. *Journal of Geophysical Research:*  
419 *Solid Earth*, 101(B6), 13883–13893. <https://doi.org/10.1029/96JB00177>
- 420 Steinberg, G. S., & Babenko, J. I. (1978). Experimental velocity and density determination of volcanic  
421 gases during eruption. *Journal of Volcanology and Geothermal Research*, 3(1–2), 89–98.  
422 [https://doi.org/10.1016/0377-0273\(78\)90005-7](https://doi.org/10.1016/0377-0273(78)90005-7)
- 423 Tournigand, P.-Y., Taddeucci, J., Gaudin, D., Peña Fernández, J. J., Del Bello, E., Scarlato, P., et al.  
424 (2017). The Initial Development of Transient Volcanic Plumes as a Function of Source  
425 Conditions. *Journal of Geophysical Research: Solid Earth*, 122(12), 9784–9803.  
426 <https://doi.org/10.1002/2017JB014907>
- 427 Van Eaton, A. R., Amigo, Á., Bertin, D., Mastin, L. G., Giacosa, R. E., González, J., et al. (2016).  
428 Volcanic lightning and plume behavior reveal evolving hazards during the April 2015 eruption  
429 of Calbuco volcano, Chile. *Geophysical Research Letters*, 43(7), 3563–3571.  
430 <https://doi.org/10.1002/2016GL068076>
- 431 Wilson, L., Sparks, R. S. J., Huang, T. C., & Watkins, N. D. (1978). The control of volcanic column  
432 heights by eruption energetics and dynamics. *Journal of Geophysical Research: Solid Earth*,  
433 83(B4), 1829–1836. <https://doi.org/10.1029/JB083iB04p01829>
- 434 Wilson, Lionel, & Self, S. (1980). Volcanic explosion clouds: Density, temperature, and particle  
435 content estimates from cloud motion. *Journal of Geophysical Research: Solid Earth*, 85(B5),  
436 2567–2572. <https://doi.org/10.1029/JB085iB05p02567>
- 437 Woods, A. W., & Bower, S. M. (1995). The decompression of volcanic jets in a crater during  
438 explosive volcanic eruptions. *Earth and Planetary Science Letters*, 131(3), 189–205.  
439 [https://doi.org/10.1016/0012-821X\(95\)00012-2](https://doi.org/10.1016/0012-821X(95)00012-2)
- 440 Barberi F, Rosi M, Sodi A (1993) Volcanic hazard assessment at Stromboli based on review of  
441 historical data. *Acta Vulcanologica* 3:173–187
- 442 Hort M, Seyfried R (1998) Volcanic eruption velocities measured with a micro radar. *Geophys Res*  
443 *Lett* 25(1):113–116. <https://doi.org/10.1029/97GL03482>

- 444 Hort M, Seyfried R, Vöge M (2003) Radar doppler velocimetry of volcanic eruptions: theoretical  
445 considerations and quantitative documentation of changes in eruptive behaviour at Stromboli  
446 volcano, Italy. *Geophys J Int* 154(2):515–32. [https://doi.org/10.1046/j.1365-](https://doi.org/10.1046/j.1365-246X.2003.01982.x)  
447 [246X.2003.01982.x](https://doi.org/10.1046/j.1365-246X.2003.01982.x)
- 448 Simkin T, Siebert L, McClelland L, Bridge D, Newhall C, Latter JH (1981) *Volcanoes of the world: a*  
449 *regional directory, gazetteer and chronology of volcanism during the last 10,000 years*. US  
450 Hutchinson Ross Publishing
- 451 Weill A, Brandeis G, Vergnolle S, Baudin F, Bilbille J, Fèvre JF, Piron B, Hill X (1992) Acoustic  
452 sounder measurements of the vertical velocity of volcanic jets at Stromboli Volcano. *Geophys*  
453 *Res Lett* 19(23):2357–2360. <https://doi.org/10.1029/92GL02502>
- 454

455 **Figure caption listing**

456 **Fig. 1** Comparison between max gas velocity, as derived from ballistic ejection velocity ( $G_v^b$ ),  
457 and directly measured maximum gas velocities ( $G_v$ ) for major to paroxysmal eruptions at  
458 Stromboli. See Table 1 for data and sources.

459 **Fig. 2** Relationships between MDR and maximum gas velocity (data points) and ballistic  
460 velocity (colored fields) for (a) normal, and (b) major and paroxysmal eruptions at Stromboli.  
461 Gray line gives fit obtained from Equation (4); red dashed lines represent the  $\sigma$  uncertainty  
462 envelope. The yellow trend is the fit to the data of Bombrun et al. (2015) and NE1 data of Harris  
463 et al. (2013), and the blue trend considers all NE crater data. Both trends look very similar, the  
464 difference with the correlation coefficient both lies in the amount of data used for each fit and  
465 because the NE2 vent data are scattered around the trendline.

466 **Fig. 3** Rank order representation of Stromboli's normal, major and paroxysmal eruptions in  
467 terms of a) the mass discharge rate and b) the maximum gas ejection rate. Both MDR rank order  
468 and  $G_v$  rank order analyses display a gap between a higher and lower group. The dashed line  
469 marks the separation between the higher ranked group composed of paroxysmal, major and ash-  
470 dominated emissions, and the lower ranked group of ballistic-dominated normal events.

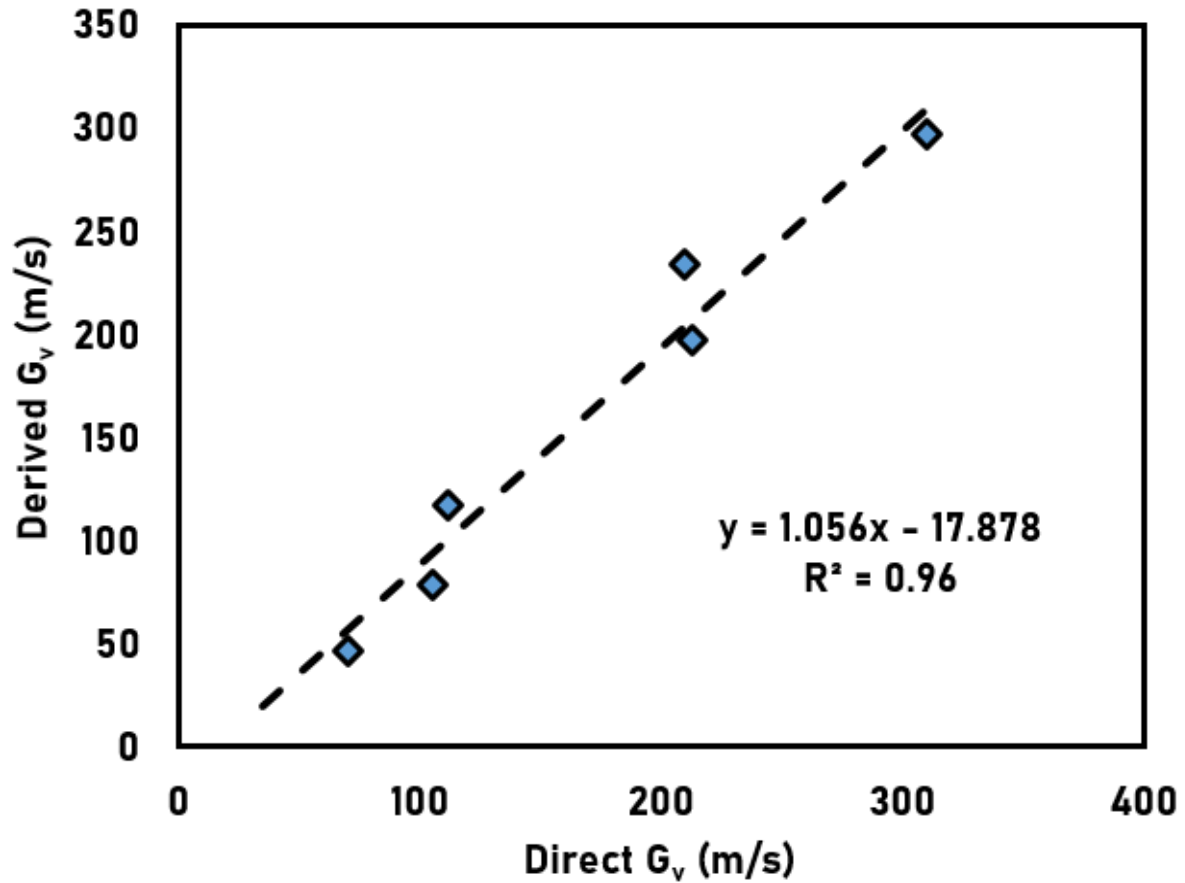
471 **Fig. 4** MDR and  $G_v$  relations. Orange field is that defined by the data for ash-dominated  
472 emissions at Stromboli, where the positive, linear increase as a function of gas density ( $d_{\text{gas}}$ ),  
473 volatile content ( $C_{\text{vol}}$ ), conduit size and vent overpressure ( $P_{\text{vent}}$ ), magma temperature (T) and  
474 silica content (X). The blue “Vulcanian-Plinian” field falls on a similar trend but is at a level  
475 two orders of magnitude higher than the “Strombolian” trend. Sakurajima, Mt. St. Helens and  
476 Pinatubo data fall within this field, all three being volcanoes associated with higher magma  
477 volatile content ( $C_{\text{vol}}$ ), silica content (X), conduit size and vent pressure ( $P_{\text{vent}}$ ) than Stromboli.

478

479 **Table caption listing**

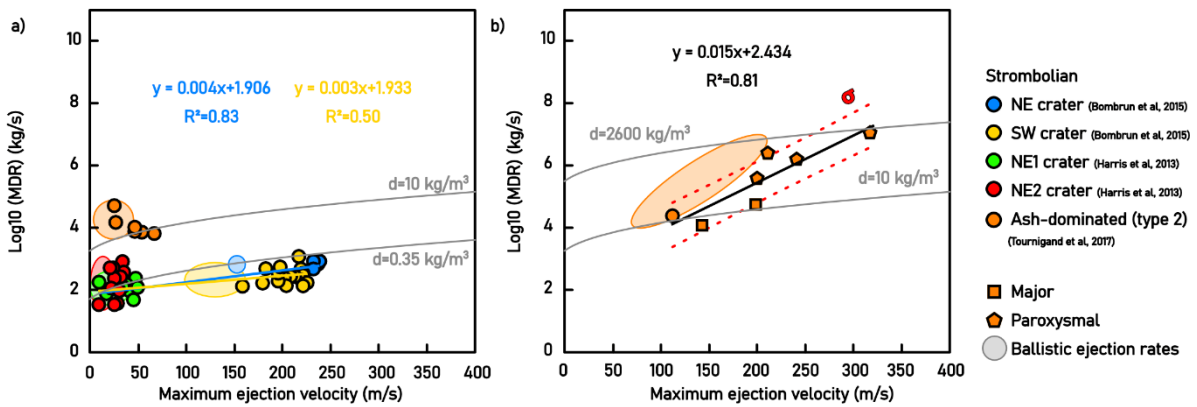
480 **Table 1** Data set for ballistic ( $B_v$ ) and gas ( $G_v$ ) velocities and mass discharge rate (MDR) for  
481 normal, major, and paroxysmal eruptions at Stromboli.  $B_v$  and  $G_v$  re-calculated using  
482 Equation (8) of Harris et al. (2012) are given in bold.

483 **Table 2** Mass and duration data obtained from thermal video for normal explosions at  
484 Stromboli's NE1 and NE2 vents (derived MDR in bold).



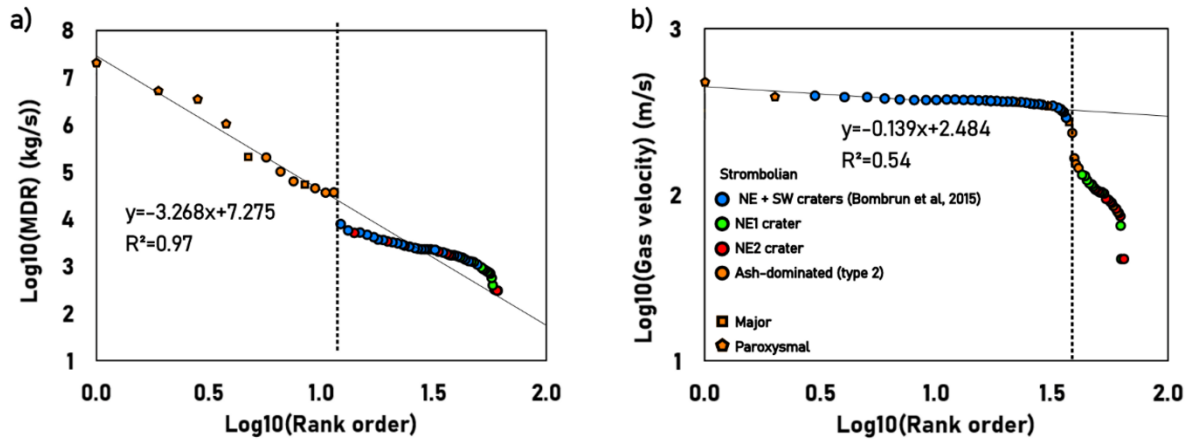
485

486 **Fig. 1**



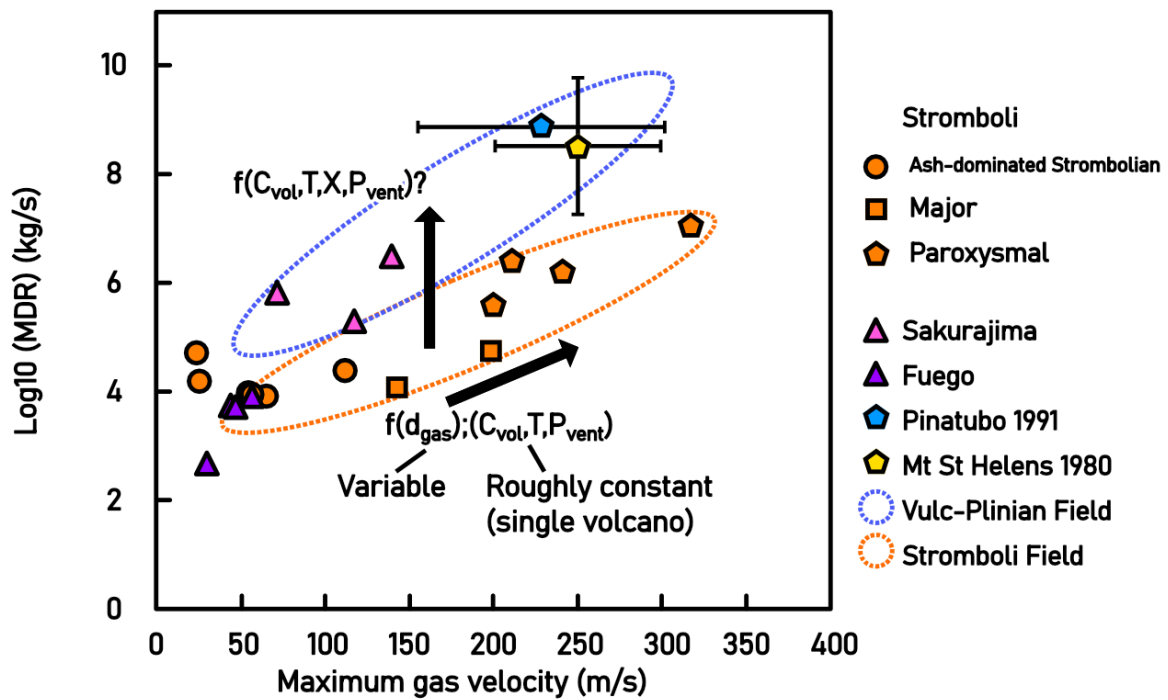
487

488 **Fig. 2**



489

490 Fig. 3



491

492 Fig. 4



493 **Table 1**

Date of eruption	Eruption type	Data type	Method	$B_v$ (m/s)	Direct $G_v$ independent measurement (m/s)	Literature derived $G_v$ calculated (m/s)	Max derived $G_v^b$ re-calculated (m/s)	Max derived $B_v$ re-calculated (m/s)	Max Mass discharge rate (kg/s)	Ref.
4/5/2003	Parox	Radiometer Seismic	Waveform delay time	200	310		<b>297</b>		1.10E+07	Rosi et al. (2006)
4/5/2003	Parox	Radiometer - Seismic	Waveform delay time	185		324	<b>276</b>			Ripepe and Harris (2008)
3/15/2007	Parox	thermal video	Particle tracking	155	210		<b>234</b>		2.20E+06	Andronico et al. (2013), Pistolesi et al. (2011)
11/8/2009	Major	Bomb mapping	ballistic model	130	n.d		<b>199</b>		1.20E+04	Gurioli et al. (2013a), Pioli et al. (2014)
11/24/2009	Major	Bomb mapping	ballistic model	90	n.d		<b>142</b>		5.50E+04	Gurioli et al. (2013a), Pioli et al. (2014)
7/3/2019	Parox	Bomb mapping	ballistic model	160	n.d	200	<b>241</b>		1.40E+06	Giordano and De Astis (2020)
8/28/2019	Parox	Bomb mapping	ballistic model	130	n.d	200	<b>199</b>		3.60E+05	Giordano and De Astis (2020)
6/27/2004	Normal	thermal video	Gas cloud and particle tracking	129	213		<b>197</b>			Harris et al. (2012)
6/2/2010	Normal	thermal video	Gas cloud and particle tracking		8-48			<b>23</b>		Harris et al. (2013a,b)
6/8/2010	Normal	thermal video	Gas cloud and particle tracking		8-35			<b>14</b>		Harris et al. (2013a,b)
6/2004	Normal	thermal video	Particle tracking	3-101			<b>158</b>			Patrick et al. (2007)
9/27/1991	Normal	acoustic sounder	Waveform analysis	20-80			<b>128</b>			Weill et al. (1992)
9/1971	Normal	high speed camera	Particle tracking	2-72	94-112		<b>117</b>			Chouet et al. (1974)
4/2000	Normal	doppler radar	Waveform analysis	44-70			<b>114</b>			Hort et al. (2003)
9/1994	Normal	thermal video	Particle tracking	35-45	40-105		<b>79</b>			Ripepe et al. (2001)
1/29/1988 to 9/8/1989	Normal	thermal video	Particle tracking	16-22	70		<b>46</b>			Ripepe et al. (1993)
10/1/1996	Normal	doppler radar	Waveform analysis	7-13			<b>34</b>			Hort and Seyfried (1998)
27/9/2012 to 18/5/2014	Normal	thermal video	Gas cloud and particle tracking			240			1.30E+03	Bombrun et al. (2015)
26/5/2013 to 26/5/2016	Normal	Visible light and thermal video	Gas cloud and particle tracking			112			5.25E+04	Tournigand et al. (2017)

495 **Table 2**

Crater	Date	Time	Maximum Velocity*	Total Mass*		Duration	MDR	Log <sub>10</sub> (MDR)
	(dd/mm/yy)	(hh:mm:ss)	(m s <sup>-1</sup> )	(x 10 <sup>3</sup> kg)		(s)	(kg/s)	(kg/s)
NE1	2/6/2010	11:35:23	16.6	1.1	1.4	18.6	<b>67</b>	1.83
NE1	2/6/2010	11:57:51	39.5	3.5	3.8	22.9	<b>160</b>	2.20
NE1	2/6/2010	12:22:35	8.3	2.7	3	18.2	<b>156</b>	2.19
NE1	2/6/2010	14:08:51	39.5	1.7	1.8	19.0	<b>92</b>	1.96
NE1	2/6/2010	14:38:43	47.8	1.7	1.9	16.4	<b>110</b>	2.04
NE1	2/6/2010	14:59:53	37.4	3.3	3.7	28.1	<b>125</b>	2.10
NE1	2/6/2010	15:48:05	43.6	1.1	1.2	27.2	<b>42</b>	1.63
NE1	2/6/2010	16:08:17	33.3	0.9	1	9.4	<b>101</b>	2.00
NE1	2/6/2010	16:12:11	47.8	1.3	1.4	6.6	<b>204</b>	2.31
NE1	8/6/2010	13:50:46	33.3	1.3	1.4	10.2	<b>132</b>	2.12
Average			34.7	1.9	2.1	17.7	119	2.0
NE2	8/6/2010	12:43:43	22.9	2.3	2.6	5.0	<b>489</b>	2.69
NE2	8/6/2010	13:29:57	29.1	0.4	0.5	5.2	<b>86</b>	1.94
NE2	8/6/2010	14:03:17	20.8	0.32	0.35	3.4	<b>99</b>	1.99
NE2	8/6/2010	14:05:23	35.3	1.9	2.1	5.2	<b>385</b>	2.59
NE2	8/6/2010	14:20:28	27	1.1	1.2	4.8	<b>239</b>	2.38
NE2	8/6/2010	15:08:56	29.1	1.1	1.2	4.6	<b>250</b>	2.40
NE2	8/6/2010	15:19:10	33.3	1.3	1.4	5.0	<b>270</b>	2.43
NE2	8/6/2010	16:32:13	33.3	3.8	4.2	5.0	<b>799</b>	2.90
NE2	8/6/2010	17:00:32	8.3	0.09	0.1	3.0	<b>32</b>	1.50
NE2	8/6/2010	18:03:52	24.9	0.56	0.63	18.6	<b>32</b>	1.50
NE2	8/6/2010	18:20:31	27	0.13	0.15	4.2	<b>33</b>	1.52
Average			26.5	1.2	1.3	5.8	247	2.2

\* data from Harris et al. (2013)

