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Characterizing magma fragmentation and its relationship with eruptive styles of Somma-Vesuvius volcano (Naples, Italy)

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Abstract

Among the active volcanoes worldwide, Somma-Vesuvius, in Italy, is one with the highest volcanic risk as the surrounding areas are highly populated. Somma-Vesuvius is guiescent since 1944, but geological and historical records revealed a frequent violent explosive activity in the last 4000 years, representing a severe risk for the actual 700000 inhabitants living in the red zone (the area having a high probability for being impacted by pyroclastic density currents) and more than one million people who can be potentially affected by tephra fallout. This study aims at analysing the distribution of tephra fallout deposits and grain-size data from several Somma-Vesuvius eruptions of different styles, ranging from Violent Strombolian to sub-Plinian and Plinian, for characterizing the associated magmatic fragmentation through the assessment of the total grain-size distribution (TGSD). Chronologically, we focus on the Avellino (4365 BP) and Pompeii (A.D. 79) Plinian eruptions, Pollena (A.D. 472) sub-Plinian eruption, and the 1906 and 1944 Violent Strombolian eruptions. The related TGSDs were estimated by means of the Voronoi tessellation method, which, beside a suitable number of local grain-size distributions, requires the delimitation of the minimum tephra loading (zero-line contour). TGSDs for the different eruptive styles are needed by tephra dispersal models for reconstructing or predicting both tephra loading and airborne ash dispersal. However, due to the typical paucity of available field outcrops, field-derived TGSDs can be biased towards the coarse and fine populations. To encompass this issue, we performed a sensitivity study on the assumption behind TGSD reconstruction and described TGSD through analytical distributions, which best fit the field TGSDs. Our main objective is a more robust estimation of the TGSDs associated with the different eruptive styles. Characterizing such TGSDs, and the other eruption source parameters, is crucial for robustly predicting tephra loading and airborne ash dispersal of future eruptions at Somma-Vesuvius.

Keywords	Total grain-size distribution; Bulk granulometry; Eruption source parameters; Tephra fallout; Volcanic hazards assessment
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Dear Executive Editor,

Please find enclosed the manuscript entitled "Characterizing magma fragmentation and its relationship with eruptive styles of Somma-Vesuvius volcano (Naples, Italy)" by Matthieu Poret, Miriana Di Donato, Antonio Costa, Roberto Sulpizio, Daniela Mele, and Federico Lucchi to be considered for publication in Journal of Volcanology and Geothermal Research. Our work provides an assessment of the total grain size distributions (TGSD) on the basis of field data analysis for different eruptive styles analysed (i.e. from Violent Strombolian to Plinian). We focused on the Avellino and Pompeii Plinian eruptions, the Pollena sub-Plinian eruption, and the 1906 and 1944 Violent Strombolian eruptions.

For achieving this aim, we analysed field-data from the literature together with new data for assessing georeferenced grain size distributions at sites representative of the proximal, medial, and distal areas. By means of this dataset, we estimated the TGSDs for the Avellino, Pollena, 1906, and 1944 eruptions. We also studied the sensitivity of the Voronoi tessellation method used for such reconstructions. Although the number of tephra samples is limited, it covers proximal, medial, and distal areas, providing the current best approximations of the TGSDs relative to each eruption. TGSDs obtained through the Voronoi tessellation method were also estimated by means of analytical distributions (i.e. as sum of i) two lognormal and ii) two Weibull distributions), which allow for extrapolating field TGSDs. By comparing the TGSDs associated with the different eruptive styles, our results indicate that increasing the eruption intensity, i.e. going from Violent Strombolian to Plinian eruptive style, and the efficiency of magma fragmentation also increases. Moreover, they also show the significance of magma-water interaction on the amount of fines of the reconstructed TGSDs.

We hope you will find this study interesting and we believe that our results stimulate further works focussing on better characterizing TGSDs of other volcanic eruptions worldwide. In particular, the estimates of the TGSD for each eruption, representative of Violent Strombolian, sub-Plinian and Plinian styles, can be used as input for numerical models aimed at reconstructing past eruptions or tephra hazard assessment for similar scenarios.

On behalf of all co-authors, we declare no competing financial interests.

We hope that the content of this article will be of a broad interest to the Journal of Volcanology and Geothermal Research.

We are looking forward to your editorial decision.

Yours sincerely,

Matthieu Poret

Matthien Parcel

Highlights

- 1 Tephra deposits of 4 different eruptions of Vesuvius were analyzed
- 2 Deposit volumes and bulk granulometries were reconstructed from field data analysis
- 3 Performed comparative study for different eruption and magma fragmentation styles
- 4 Results are important for tephra dispersal modelling and hazard assessment purposes

Characterizing magma fragmentation and its relationship with eruptive styles of Somma-Vesuvius volcano (Naples, Italy)

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9 Abstract

Among the active volcanoes worldwide, Somma-Vesuvius, in Italy, is one with the highest volcanic risk as the surrounding areas are highly populated. Somma-Vesuvius is quiescent since 1944, but geological and historical records revealed a frequent violent explosive activity in the last 4000 years, representing a severe risk for the actual 700000 inhabitants living in the red zone (the area having a high probability for being impacted by pyroclastic density currents) and more than one million people who can be potentially affected by tephra fallout. This study aims at analysing the distribution of tephra fallout deposits and grain-size data from several Somma-Vesuvius eruptions of different styles, ranging from Violent Strombolian to sub-Plinian and Plinian, for characterizing the associated magmatic fragmentation through the assessment of the total grain-size distribution (TGSD). Chronologically, we focus on the Avellino (4365 BP) and Pompeii (A.D. 79) Plinian eruptions, Pollena (A.D. 472) sub-Plinian eruption, and the 1906 and 1944 Violent Strombolian eruptions. The related TGSDs were estimated by means of the Voronoi tessellation method, which, beside a suitable number of local grain-size distributions, requires the delimitation of the minimum tephra loading (zero-line contour). TGSDs for the different eruptive styles are needed by tephra dispersal models for reconstructing or predicting both tephra loading and airborne ash dispersal. However, due to the typical paucity of available field outcrops, field-derived TGSDs can be biased towards the coarse and fine populations. To encompass this issue, we performed a sensitivity study on the assumption behind TGSD reconstruction and described TGSD through analytical distributions, which best fit the field TGSDs. Our main objective is a more robust estimation of the TGSDs associated with the different eruptive styles. Characterizing such TGSDs, and the other eruption source parameters, is crucial for robustly predicting tephra loading and airborne ash dispersal of future eruptions at Somma-Vesuvius.

32 Keywords: Total grain-size distribution; Bulk granulometry; Eruption source parameters; Tephra
 33 fallout; Volcanic hazards assessment

1 Introduction

The Somma-Vesuvius volcanic complex is one of the most studied volcanoes in the world, and is included among the highest volcanic risks in the world (e.g. Macedonio et al., 2008). One of the main goals of modern volcanology is a quantitative assessment of volcanic hazards (e.g. tephra loading, airborne ash dispersal) in sensitive areas like those surrounding Somma-Vesuvius, where they can heavily impact the metropolitan city of Naples (Italy) with potential severe consequences for the central Mediterranean zone (Folch and Sulpizio, 2010; Sulpizio et al., 2014). For a robust volcanic hazard assessment, we must know the eruptive history of the volcano and its past behaviour (e.g. Cioni et al., 2008; Santacroce et al., 2008). Such information derives typically from the analysis of geological records (e.g. Cioni et al., 1999; 2008; Santacroce and Sbrana, 2003; Santacroce et al., 2008; Gurioli et al., 2010; Sulpizio et al., 2010a; 2010b; 2010c; 2010d; 2014). In fact, analysis of geological data allows assessing the key eruption source parameters (ESP) associated with an eruption, such as the total erupted mass (TEM; i.e. eruption magnitude), mass eruption rate (MER; i.e. eruption intensity), eruptive column height, and total grain-size distribution (TGSD), which depends on the intensity and behaviour of the initial magma fragmentation (Bonadonna and Houghton, 2005; Bonadonna et al., 2015; Costa et al., 2016). To investigate the effect of different magma compositions and eruption intensity on ESPs, we selected four eruptions from the eruptive record of Somma-Vesuvius, representative of its most frequent eruptive styles. In particular, we considered the Avellino Plinian eruption (c.a. 3900 years BP; Sevink et al., 2011), the Pollena sub-Plinian eruption (A.D. 472; Sulpizio et al., 2005; Santacroce et al., 2008; Foch and Sulpizio, 2010), and the Violent Strombolian eruptions of 1906 (Mercalli, 1906; Arrighi et al., 2001) and 1944 (Imbò, 1949; Cubellis et al., 2013). Moreover, for comparison purposes, we also considered the TGSD of the Pompeii Plinian eruption (A.D. 79) derived from Macedonio et al. (1988; 2008). The literature reports petrochemical and lithological features of the tephra deposits for these four eruptions (e.g. Imbò, 1949; Macedonio et al., 1988; Arrighi et al., 2001; Cioni et al., 1999; 2003a; 2003b; 2004; 2008; Sulpizio et al., 2005; 2007; 2008; 2010a; 2010b; 2010c; 2010d; 2012; 2014; Cole and Scarpati, 2010; Cubellis et al., 2013; Barsotti et al., 2015).

This study aims at bringing together geological data from different eruptions of different styles at Somma-Vesuvius to assess and compare the relative magma fragmentation processes, and characterize their ESPs, which is pivotal for robustly predicting tephra loading and airborne ash dispersal of future eruptions. Moreover, the quantification of TGSD, including ash, for each eruption can be used as an indicator for comparing the magma fragmentation efficiency during the different eruptions, and its effect on the eruptive style at Somma-Vesuvius.

Assessing TGSD is also very important for characterizing the eruptive style by associating particle size distribution to the initial gas content and magma-water interaction processes (e.g. Kaminski and Jaupart, 1998, Rust and Cashman, 2011, Costa et al., 2016). Commonly, TGSD is required as key input parameter within tephra dispersal models for reconstructing or predicting the tephra loading and airborne ash dispersal (e.g. Folch, 2012), and to produce risk mitigation strategies (Folch et al., 2008; Scollo et al., 2008) for future eruptions (e.g. at Somma-Vesuvius). In this study, the TGSDs of the Avellino, Pollena, 1906, and 1944 eruptions, from Plinian to sub-Plinian and Violent Strombolian, are assessed by means of the Voronoi tessellation method (Bonadonna and

- Houghton, 2005), which integrates individual georeferenced grain-size distributions (GSD) for each eruption. We also focussed on estimating the fraction of particle matter finer than 10 um (hereinafter PM_{10}) numerically needed for assessing the content of airborne ash (Poret et al., 2018b), which can potentially affect aviation (e.g., Folch and Sulpizio, 2010; Folch et al., 2012; Sulpizio et al., 2012).
- However, determining TGSD from field samples analysis only can have strong limitations due to the sampling distance from the vent (Costa et al., 2016; Poret et al., 2018b) and the spatial and density distribution of samples along the main axis of the tephra plume (Bonadonna and Houghton, 2005; Bonadonna et al., 2015; Spanu et al., 2016). In fact, field-derived TGSD typically tends to underestimate the fraction of either or both the coarse and fine populations (Bonadonna and Houghton, 2005; Rose and Durant, 2009; Scollo et al., 2014; Costa et al., 2016). For encompassing these issues and assessing the related uncertainties we carried out a sensitivity analysis and also described the TGSD as the sum of two lognormal (Gaussian in Φ) and then two Weibull distributions by best fitting the field-based TGSDs (Costa et al., 2016, 2017; Poret et al., 2017; 2018b; Mueller et al., 2019; Pedrazzi et al., 2019).

¹⁴⁷/₁₄₈ 94 2 Eruptive history summaries of Somma-Vesuvius and selected eruptions

The Somma-Vesuvius eruptive history showed alternating effusive and explosive eruptions, sometimes associated with destructive phases (caldera) of the volcanic edifice. In particular, four Plinian eruptions with caldera collapses truncated the Mt. Somma volcano, forming the present-day summit caldera (Cioni et al., 1999; 2008; Rolandi et al., 2004; Santacroce et al., 2008). Chronologically, these are the Pomici di Base $(22.03 \pm 0.18 \text{ cal ky BP}; \text{Bertagnini et al., } 1998;$ Santacroce et al., 2008), Mercato (8.89 ± 0.09 cal ky BP; Santacroce et al., 2008; Mele et al., 2011), 156 100 Avellino $(3.90 \pm 0.04 \text{ cal ky BP}; \text{Sevink et al., 2011}; \text{Sulpizio et al., 2010})$, and Pompeii (A.D. 79; Sigurdsson et al., 1985) eruptions. After the Pompeii eruption, the Vesuvius cone started to grow 160 103 within the Mt. Somma caldera reaching its present shape (Cioni et al., 2008). Nonetheless, among 161 104 the recorded post-Pompeii activities, several high-intensity explosive eruptions occurred at Somma-Vesuvius partly modifying the structure of the cone. These are the sub-Plinian Pollena (A.D. 472; ₁₆₄ 106 Sulpizio et al., 2005) and A.D. 1631 (Poret et al., 2019) eruptions. The most recent period of activity (between A.D. 1631–1944) was characterised by recurrent summit and lateral lava effusions 165 107 166 108 associated with semi-persistent and mild explosive activity, interrupted by pauses lasting from months to a maximum of seven years (Santacroce, 1987; Cioni et al., 2008). During this period, 169 110 Vesuvius produced a few Violent Strombolian eruptions, such as in 1906 and 1944. In terms of eruption magnitudes (i.e. erupted volume), the literature for the Somma-Vesuvius eruptions reports 170 111 volumes ranging from 1 to 10 km³ for Plinian, 0.01 to 1 km³ for sub-Plinian, and 0.001 to 0.01 km³ for Violent Strombolian eruptions (Cioni et al., 2008).

Hereinafter, we report a synthetic description of the main features of the eruptions considered in the ₁₈₂ 115 present study.

2.1 Avellino and Pompeii Plinian eruptions 184 116

The Avellino eruption $(3.90 \pm 0.04 \text{ cal ky BP}; \text{Sevink et al., 2011})$, was subdivided in three eruptive 186 117 phases: opening, magmatic Plinian, and phreatomagmatic (Sulpizio et al., 2010b; 2010c; Massaro et al., 2018). During the opening phase, a transient short-lived eruptive column reached 12-20 km, followed by the formation of pyroclastic density currents (PDC) from partial or total collapse of the 190 120 191 121 eruptive column (Sulpizio et al., 2010c). The magmatic Plinian phase produced a sustained eruptive column growing with time from 22 to 30 km. This phase ejected the main volume of tephra estimated at 1.4 km³, which was dispersed mostly north-eastwards (Cioni et al., 2003a; Sulpizio et al., 2008; 2010c). Finally, the phreatomagmatic phase was dominated by PDC deposits, which 195 124 significantly contributed to the total erupted volume with $\sim 1 \text{ km}^3$ (Sulpizio et al., 2008; 2010a; 2014; Gurioli et al., 2010). It is worth noting that tephra from the Plinian phase was recovered as far as in Albania (Fig. 1), where they occur within the sedimentary succession of Shkodra lake (~430 199 127 200 128 km from the source; Sulpizio et al., 2010a).



Fig. 1: Map of the main outcrops of the Avellino, Pollena, 1906, and 1944 Somma-Vesuvius eruptions. The left-bottom inset zooms onto the proximal area. Coloured lines refer to the dispersal area for each eruption, modified after Sulpizio et al., 2010a, 2010b; 2010c; 2014 for Avellino; Sulpizio et al., 2005; 2010a; 2014 for Pollena; Arrighi et al., 2001; Barsotti et al., 2015 for 1906; and Imbò, 1949; Cole and Scarpati, 2010; Cubellis et al., 2013 for 1944. SL, OL, and PL refer respectively to the Shkodra, Ohrid, and Prespa lakes (Albania and FYROM). For the interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.

Concerning the Pompeii (A.D. 79) Plinian eruption of Somma-Vesuvius, very famous for the destruction of the Roman towns of Pompeii and Herculaneum, the volcanological aspects have been described by numerous authors (e.g. Sigurdsson et al., 1985, Carey and Sigurdsson, 1987, 225 137 Macedonio et al., 1988; Pfeiffer et al., 2005). After a short initial phreatomagmatic vent-opening phase, the eruption was characterized by a purely magmatic phase with a high sustained eruption 229 140 column, which was subdivided into a lower layer of white phonolitic pumice (White Pumice) and 230 141 an upper tephritic-phonolitic pumice fall (Gray Pumice) deposit. This phase ended column collapse and the emplacement of pyroclastic flows, which was followed by \Box phreatomagmatic activity and the emplacement of lithic-rich breccia and pyroclastic surges, interpreted as the consequence of decreasing pressure in the vent and magma-water interaction. For the White and the Gray units, 234 144

Sigurdsson et al. (1985) estimated, respectively, 2.5×10^{12} and 6.5×10^{12} kg of tephra, or 1 and 2.6 km³ DRE. Concerning the column height, they estimated that during the White Pumice phase it increased from about 15 to 26 km, while during the Gray phase, it reached to a maximum of 32 km and then decreased to about 27 km.

²⁴⁵₂₄₆ 149 *2.2 Pollena sub-Plinian eruption*

237 238

247 The Pollena eruption (A.D. 472) is the major sub-Plinian event of Somma-Vesuvius, and is 150248 considered by Italian Civil Protection as one of the reference scenarios in case of renewal of 249 151 250 152 explosive activity. Sulpizio et al. (2005) described the eruption through three phases (i.e. opening, 251 153 magmatic and phreatomagmatic), with a similar eruptive evolution to that described for the Plinian 252 events. In particular, the Pollena eruption was characterized by a highly unstable MER during the 154 253 254 155 opening phase, resulting in eruptive column pulses with general dispersal of the tephra fallout ²⁵⁵ 156 deposit towards north-east. Then, during the magmatic phase, at least two dominant pulses of high 256 157 eruptive intensity are recorded by the deposition of pyroclastic fall beds and by the signature of 257 258 158 dilute and dense PDCs (Sulpizio et al., 2005). The MER reached a peak intensity of $\sim 3.4 \times 10^7$ kg/s during this phase, in particular during the emplacement of the L₈ fallout bed, which is the most 259 159 260 160 dispersed (Sulpizio et al., 2005). The final phreatomagmatic phase was characterized by a pulsating 261 column and emplacement of diluted to concentrated PDCs. 161 262

263 162 The tephra fallout deposits dispersed north-eastwards (Fig. 1; see also Sulpizio et al., 2005), while 264 the PDCs deposited mainly on the northern slopes of the volcano. It is worth noting that fine ash 163 265 reached the Balkans, being identified in the sedimentary succession of the Shkodra lake (~440 km 266 164 267 165 from the source; Sulpizio et al., 2010a), and as crypto-tephra in Ohrid lake (Sulpizio et al., 2010c). 268 166 Sulpizio et al. (2005) estimated the volume of the pyroclastic fall deposits around 0.44 km³ using 269 ₂₇₀ 167 the proximal isopachs. Such a volume increases up to ~1.38 km³ and the maximum column height 271 168 around 28 km by adding data from distal sites (Sulpizio et al., 2005).

²⁷³ 169 **2.3 The 1906 and 1944 Violent Strombolian eruptions**

275 170 The 1906 and 1944 eruptions are examples of Violent Strombolian eruptions at Somma-Vesuvius, 276 which are typically characterized by emplacement of lava flows in the early phases followed by 171 277 explosive activities (Imbò, 1949; Cioni et al., 2008). The latter phases of the eruptions typically 278 172 ²⁷⁹ 173 consist of intense lava fountaining episodes associated with eruptive columns rising up to several 280 174 kilometre heights. Sometimes, a phreatomagmatic phase closed the activity, accompanied by ash 281 emissions. The Violent Strombolian eruptive style is considered the most likely scenario in the case 282 175 283 176 of a possible future reactivation of Somma-Vesuvius (Marzocchi et al., 2004; Neri et al., 2008). In 284 177 particular, the eruptions of 1906 and 1944 produced tephra deposits of metric thickness in proximal 285 areas, with distal ash deposits recognized as far as in Albania (Cubellis et al., 2013). 178286

Several overviews and details of the 18-day long 1906 eruption are available in the literature (e.g. De Lorenzo, 1906; Mercalli, 1906; Sabatini, 1906; Perret, 1924; Bertagnini et al., 1991; Scandone et al., 1993; Barsotti et al., 2015). The eruption started with a 4-day effusive-explosive phase; then an intense lava fountaining episode occurred and the Violent Strombolian phase started, lasting 2 days (Mercalli, 1906; Barsotti et al., 2015 – Phase I) and producing a column that reached ~13 km

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298 above the vent (Perret, 1924; Scandone et al., 1993). Ash emissions dispersed towards the Adriatic 184 299 ₃₀₀ 185 Sea (Arrighi et al., 2001) and Montenegro (~400 km from the vent: De Lorenzo, 1906: Barsotti et al., 2015), as shown by the tephra fallout extent displayed in Fig. 1. Finally, a 12-day long phases of 301 186 ³⁰² 187 ash emission (Barsotti et al., 2015 - Phase II) occurred releasing abundant reddish-grey fine ash 303 188 together with millimetre-sized accretionary lapilli (De Lorenzo, 1906; Mercalli, 1906). Wind 304 conditions alternatively dispersed ash over the city of Naples and surroundings (Hobbs 1906). 305 189 Sabatini (1906) estimated a minimum tephra fallout volume of ~0.21 km³ and Barsotti et al. (2015) 306 190 ³⁰⁷ 191 reported a TEM of 1.34×10^{11} kg. Furthermore, they mention a MER of 10^{6} and 10^{5} kg/s for Phase 308 ₃₀₉ 192 I and II respectively, i.e. a bulk MER of 10^6 kg/s. Sulpizio et al. (2012) estimated a TEM at 9.3 \times 10^{10} kg and a fallout mass of 3.7×10^{10} kg. For a duration of 18 days, the average MER is estimated 310 193 311 194 at 6×10^4 kg/s. In contrast, Cioni et al. (2008; references therein) report a peak MER of 3.4×10^5 312 195 kg/s for the basal lapilli bed and 5.4×10^6 kg/s for the paroxysmal phase. 313

314 196 The 17-day long 1944 eruption started with the emplacement of lava flows mainly towards the 315 197 north slopes of the actual Vesuvius cone. The subsequent explosive phase comprises a series of 8 316 ₃₁₇ 198 lava fountains over a time interval of ~8 h (Arrighi et al., 2001). Scandone et al. (1993) report for 318 199 this phase a steady eruptive column that reached ~5 km above the vent and ejected ash into the 319 200 atmosphere (Macedonio et al., 2008). In particular, Imbò (1949) provided information relative to 320 201 the meteorological conditions. The tephra was transported towards south-east (Fig. 1), reaching 321 322 202 Albania where ash fallout has been observed in Devoli (Cubellis et al., 2013). Cioni et al. (2008) 323 203 estimated the erupted volume at ~0.066 km³ from the isopachs map produced by Pesce and Rolandi 324 204 (2000). Based on the TEM estimated at 2.2×10^{12} kg and the eruption duration (17 days), the 325 205 average MER is estimated at 1.5×10^6 kg/s (Cioni et al., 2008). Differently, Scandone et al. (1986) 326 report a MER of 4×10^5 kg/s, whereas Macedonio et al. (2008) estimated the MER at 5×10^5 kg/s 327 206 328 207 for modelling tephra fallout. 329

³³⁰ 208 3 Data and Methodology

³³²₃₃₃ 209 3.1 Field data

334 335 210 To reconstruct the dispersal of tephra deposits of the studied eruptions (Fig. 1), we used geological data from literature (e.g. Imbò, 1949; Arrighi et al., 2001; Cioni et al., 2003a; Sulpizio et al., 2005; 336 211 337 212 2007; 2010a; 2010b; 2010c; 2010d; 2012; 2014; Cole and Scarpati, 2010; Cubellis et al., 2013; 338 213 Barsotti et al., 2015). Throughout the manuscript, we will use the terms proximal, medial, and distal 339 for indicating the areas affected by tephra at different distances. Nonetheless, these zones reflect the 340 214 341 215 distance from the vent and strongly depend on the eruption intensity (i.e. the column height) 342 216 together with the atmospheric conditions (e.g. wind fields). Costa et al. (2016) proposed to consider 343 ₃₄₄ 217 distances from 1/10 to 10 times the eruptive column height to define the proximal, medial, and distal deposits, for adequately sampling the whole tephra fallout up to 125 µm (although such 345 218 346 219 distances depend on wind conditions as discussed in their work). In this study, for the sake of 347 220 simplicity, we use the term proximal to indicate distances from the source up to 30 km, medial for 348 distances of 30-200 km, and distal for distances > 200 km. 349 221

Field data comprise tephra samples collected for the Avellino, Pollena, 1906, and 1944 eruptions (Fig. 1; Table 1). All the details are available as Supplementary Material (Tables S1, S2, S3, and S4)

353 354

respectively for the Avellino, Pollena, 1906, and 1944 eruptions). Regarding the Avellino eruption, we used 9 samples distributed from proximal (samples 1-2), to medial areas (samples 3-8) derived from Sulpizio et al. (2010b), and a distal one in the Shkodra lake (sample 9; Sulpizio et al., 2010a). 360 226 361 227 The Pollena fallout deposits were characterized using 8 samples distributed in proximal (samples 1-5), medial (samples 6-7), and distal areas (sample 8 in the Shkodra lake, Albania; Sulpizio et al., 364 229 2010a). Recently, ash related to the Pollena eruption was also reported as crypto-tephra in the Ohrid 365 230 lake (Albania and FYROM border; Vogel et al., 2009; Sulpizio et al., 2010d), expanding significantly the tephra deposit eastwards (Fig. 1). However, the lack of grain-size analysis prevents from integrating data for this outcrop.

Table 1: Field measurements (i.e. location, distance from the vent, main mode, and loading) used for the grain-size analysis and TGSD estimations of the Avellino, Pollena, 1906, and 1944 eruptions at Somma-Vesuvius. Sample locations are shown in Fig. 1. Details of the field data are available as Supplementary Material (Tables S1, S2, S3, and S4).

373	Samples		Field observations			
374 -		x •/ 1	X X	Distance	NF N (E)	X P A (A)
375	Avellino	Longitude	Latitude	(km from source)	Mode (Φ)	Loading (kg/m ²)
376	Av-1	14.447	40.867	5	-3	1.80 × 10 ²
377	Av-2	14.611	40.971	23	-2	1.40×10^{2}
070	Av-3	14.245	41.223	47	3	3.00×10^{1}
378	Av-4	15.091	41.151	67	1	1.20×10^{2}
379	Av-5	14.661	41.654	94	2	4.00×10^{1}
380	Av-6	14.305	42.001	131	5	3.00×10^{1}
201	Av-7	13.385	41.974	155	4	3.00×10^{1}
301	Av-8	16.619	40.388	191	5	3.00×10^{1}
382 _	Av-9	19.232	42.228	430	5	1.00 × 10 ¹
383	Pollena					
384	Po-1	14.454	40.849	4	-3	3.84×10^{2}
385	Po-2	14.477	40.879	8	-2	1.30×10^{2}
000	Po-3	14.524	40.839	9	-3	1.40×10^2
386	P0-4	40.848	14.538	10	-3	1.30×10^2
387	P0-5	14./08	40.899	25	-1	1.08×10^{2}
388	F0-0 Po 7	15.005	40.950	130	23	3.50×10^{-1}
380	Po-8	19.440	42.001	440	5	1.00×10^{-5}
300 _	1906	17.440	42.070	110	0	5.00 ** 10
201	1906 1	14 473	40 823	4	2	5 50 × 102
391	1906-2	14.475	40.825	+ 5	-2 -2	5.50×10^{2}
392	1906-3	14 506	40.833	7	-2	2.75×10^2
393	1906-4	14.526	40.859	10	-2	1.10×10^2
394	1906-5	14.567	40.891	14	-3	1.10×10^{2}
205	1906-6	14.946	40.887	44	1	1.10×10^{1}
395	1906-7	15.258	41.019	72	2	5.50×10^{0}
396	1906-8	15.605	40.931	100	3	2.20×10^{0}
397	1906-9	17.388	41.173	252	3	4.40 × 10 ⁰
398	1944					
300	1944-1	14.473	40.823	4	-2	6.00 × 10 ²
400	1944-2	14.464	40.856	5	-2	6.00×10^{2}
400	1944-3	14.506	40.833	7	-1	3.00×10^{2}
401	1944-4	14.526	40.859	10	-1	1.20×10^{2}
402	1944-5	14.567	40.891	14	-3	1.00×10^{1}
403	1944-6	14.946	40.887	44	1	1.20×10^{1}
40.4	1944-7	15.258	41.019	72	2	6.00×10^{0}
404	1944-8	19.883	40.814	460	5	1.20×10^{0}
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416 237 For the 1906 and 1944 Violent Strombolian eruptions, 7 samples were collected at the same 417 locations (Table 1), representing the proximal (samples 1-5) and medial areas (samples 6-7). Then, 238 418 the samples 8 and 9 of the 1906 eruption were collected in the Monticchio lake and in a marine core 419 239 420 240 offshore the city of Bari (Fig. 1), located at ~100 and ~252 km from the source respectively. The 421 241 data related to these samples are reported in Fig. 1 and Table 1. For the 1944 eruption, the farthest 422 sample (sample 8) was collected in Devoli (Albania; Cubellis et al., 2013), which is ~460 km from 423 242 424 243 the vent.

426 244 *3.2 Estimating the TGSDs*

428 245 Sampling data include measurements of the tephra loading at several sites (Fig. 1 and Table 1), 429 430 246 which were sieved for assessing the GSDs relative to the affected areas. The sieving method gives GSD from -5 to 5 Φ (Poret et al., 2018a), where $\Phi = -\log_2 d$ with d is the particle diameter in 431 247 432 248 millimetre (Krumbein, 1934). Meanwhile, fine ash was analysed through the Beckman Coulter 433 434 249 Counter MultisizerTM 4 at the University of Bari, Italy. The latter method gives GSD from 3 to 7 Φ , 435 250 extending the grain-size analysis towards the tail of the distribution relative to fine ash. The 436 251 resulting normalized GSD is obtained by integrating the two partial GSDs taking the sieving 437 438 252 method as reference. A similar procedure was successfully used in Poret et al. (2018b) for grain-439 253 size purposes integrating complementary methods. Each GSD includes tephra information relative 440 254 to the bombs (or blocks; diameter $d \ge 64$ mm), lapilli (2 mm $\le d < 64$ mm), and ash (d < 2 mm). 441 We further distinguish coarse ash, $64 \ \mu m \le d < 2 \ mm$, and fine ash, $d < 64 \ \mu m$ (e.g., Folch, 2012). 255 442

443 256 Among the several integration methods existing for estimating TGSD (e.g. weighted average, 444 257 Walker et al., 1981; sectorization of the deposit, Carey and Sigurdsson, 1982; isomass maps, 445 446 258 Murrow et al., 1980), in this study we use the Voronoi tessellation method (Bonadonna and 447 259 Houghton, 2005), considering its advantages and limitations (Bonadonna and Houghton, 2005; 448 260 Bonadonna et al., 2015; Costa et al., 2016; Spanu et al., 2016; Poret et al., 2018a; 2018b). The 449 method consists in dividing the pyroclastic deposit into Voronoi polygons associated with each 261 450 georeferenced GSD (i.e. each sample). Then, TGSD is obtained as the weighted average of the mass 451 262 452 263 distribution over the Voronoi cells, which refer to the entire deposit. Prior to apply this method, it is 453 264 fundamental to define the areal extent of the tephra deposit through assessment of the zero-line 454 contour, which is the line at which the deposit thickness can be assumed negligible (literally equal 265 455 456 266 to zero; Bonadonna and Houghton, 2005). In the studied cases, we used the data from the literature 457 267 to assess the zero contours (see Fig. 1). Starting from the field-based TGSDs of the different 458 268 eruptions, we also inferred the TGSDs by means of general analytical distributions (Costa et al., 459 2016; 2017). First, we considered the sum of two lognormal distributions (hereinafter bi-Gaussian 460 269 461 270 in Φ -units):

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 $f_{bi-Gaussian}(\Phi) = p \frac{1}{\sigma_1 \sqrt{2\pi}} e^{-\frac{(\Phi - \mu_1)^2}{2\sigma_1^2}} + (1 - p) \frac{1}{\sigma_2 \sqrt{2\pi}} e^{-\frac{(\Phi - \mu_2)^2}{2\sigma_2^2}}$

where Φ denotes particle diameter, *p* and (1-*p*) are, respectively, the coarse and fine sub-population weights, and μ_1 , μ_2 and σ_1 , σ_2 denote the mean and standard deviation of the two Gaussian distributions in Φ -units. Then, we used two Weibull distributions (Costa et al., 2016; 2017):

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 $f_{bi-Weibull}(d) = q \frac{1}{n_1^{\frac{1}{n_1}} \Gamma\left(1 + \frac{1}{n_1}\right)^{\lambda_1}} \left[\frac{d}{\lambda_1}\right]^{n_1} e^{-\frac{1}{n_1}\left(\frac{d}{\lambda_1}\right)^{n_1}} + (1-q) \frac{1}{n_2^{\frac{1}{n_2}} \Gamma\left(1 + \frac{1}{n_2}\right)^{\lambda_2}} \left[\frac{d}{\lambda_2}\right]^{n_2} e^{-\frac{1}{n_2}\left(\frac{d}{\lambda_2}\right)^{n_2}}$

276 where d denotes particles diameter, q and (1-q) are, respectively, the coarse and fine sub-population 277 weights, and λ_1 , λ_2 and n_1 , n_2 are the scale and shape parameters of the two distributions.

278 4 Results and discussions

4.1 Individual grain-size distributions 279

489 490 280 The results for the individual GSDs are displayed in Figs. 2, 3, 4 and 5, respectively for the 491 281 Avellino, Pollena, 1906, and 1944 eruptions. First of all, it is worth noting that all the TGSD ⁴⁹² 282 reconstructions (Fig. 6) reflect the limitations associated with the available tephra samples in terms 493 of number and spatial distribution. Moreover, such a reconstruction suffers from the fact that all 283 494 495 284 kinds of tephra particles are considered together, without distinguishing for the different lithologies, ⁴⁹⁶ 285 which can have different settling behaviours. However, the reconstructed TGSDs represent the best 497 286 approximations of the initial magma fragmentation for each of the studied eruptions. 498

499 287 Regardless of the eruption, the GSDs at each location show a unimodal distribution with a clear 500 288 shift of the mode from proximal to distal areas. Such features have been typically observed for 501 502 289 several tephra fallout deposits (e.g. Durant et al., 2009; 2010 for the 1980 Mt. St. Helens eruption; 503 290 Watt et al., 2015 for the Chaiten eruption). Considering the proximal samples (Fig. 1; Table 1), 504 291 regardless of the eruption, the modes range from -3 to 0 Φ (Table 1), with similar size and 505 ₅₀₆ 292 proportions, indicating a dominancy of lapilli and coarse ash up to 30 km from the source, typically having relatively high terminal velocities, and thus depositing near the volcano (Bonadonna and 507 293 508 294 Costa, 2013). Regarding the medial areas, the modes range from 1 to 6 Φ (Table 1), covering a 509 295 larger grain-size range than in the proximal area due to a larger sampling distance range (i.e. ~44-510 191 km from the source), different eruptive column heights (3-30 km), and wind intensities (Costa 511 296 512 297 et al., 2016). In particular, for the Pollena, 1906, and 1944 eruptions, the modes vary from 1 to 3 Φ 513 298 (see Figs. 3, 4, 5, and Table 1), whereas the Avellino eruption has medial modes up to 6 Φ (Fig. 2 514 515 299 and Table 1). Indeed, only the Avellino eruption deposits have medial samples up to ~191 km from 516 300 the vent. Furthermore, samples at similar distances from the source tend to indicate the same 517 301 modes, being consistent with the main findings of Spanu et al. (2016). Considering the distal 518 ₅₁₉ 302 samples, modes range between 5 to 6 Φ , except for the 1906 distal sample (i.e. 3 Φ ; Fig. 4 and 520 303 Table 1), which is closer to the vent than for the other eruptions (i.e. ~252 km from the source ⁵²¹ 304 instead of ~430-460 km). It is worth noting that the relative GSDs indicate a good preservation of 522 305 the tephra fallout for the studied eruptions, mostly made of fine ash (including PM_{10}) collected 523 524 306 beyond the Apennines and Adriatic Sea up to Albania and Montenegro (Fig. 1; Sulpizio et al., 525 307 2010a; 2010d).

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⁵⁹³ 312 Considering the similarities observed in the evolution of the Plinian and sub-Plinian eruptions (see ₅₉₅ 313 Sect. 2), we compare the GSDs of the Avellino (Plinian) and Pollena (sub-Plinian) eruptions (i.e. Figs. 2 and 3). The proximal areas show similar modes (i.e. -3 Φ at ~5 km from the source and 596 314 between -2 and -1 Φ at ~25 km), proportions and sizes. Furthermore, we compare the proximal ₅₉₉ 316 GSDs of these eruptions with those of the Pompeii Plinian eruption reported in Macedonio et al. (1988) and collected in Pompeii (~11 km), Castellammare (~15 km), and Maiori (~25 km) 600 317 respectively. GSDs have modes at -3 Φ , except for Maiori which peaks at -2 Φ , being consistent with the results associated with the Avellino and Pollena eruptions. In the medial zone, samples for the two eruptions located at ~100 km from the source peak at 2 Φ , and those at ~130 km have 604 320 modes at 5 and 3 Φ (Table 1), respectively for Avellino and Pollena eruptions. According to Subjiction of Subjiction Subjictin Subjiction Subjiction Subjiction Subjiction Subjictin 608 323 proportions in fines occurred during the Avellino eruption, especially during the magmatic Plinian ⁶⁰⁹ 324 phase. The distal modes for the two eruptions peak between 5 and 6 Φ for samples located in the Shkodra lake (Albania; Sulpizio et al., 2010a), indicating relatively the same atmospheric conditions and intensity of magma fragmentation leading to a tephra dispersal towards north-east. It 613 327 is worth noting that interpreting grain-size relative to fine ash in terms of intensity of fragmentation is complex as the energy released at fragmentation depends on the sum of different contributions and the mechanical strength of the magma (Büttner et al., 2006).

Then we compared the GSDs of the 1906 and 1944 Violent Strombolian eruptions (Figs. 4 and 5), noting that for the proximal and medial areas the tephra fallout appears to be similar in size and 620 332 proportion for the same sampling sites (i.e. samples 1-7). Nonetheless, the presence of fine ash at 621 333 very proximal distance from the vent (i.e. < 4 km) suggests the likely occurrence of ash aggregation (Costa et al., 2010; Folch et al., 2010), which appears as disaggregated fine ash at the ground (Mueller et al., 2017). This observation is supported by Arrighi et al. (2001). The modes change in distal areas peaking at 3 and 5 Φ respectively for the 1906 and 1944 eruptions (Table 1), due to 625 336 different distances from the vent, respectively ~252 and ~460 km. The literature reports the tephra fallout of the 1906 eruption in Montenegro (De Lorenzo, 1906; Barsotti et al., 2015; Fig. 1), but 629 339 without the possibility of assessing the grain-size distribution due to very thin deposits.



Fig. 5: Individual field grain-size distributions (samples 1944-x) for the 1944 Violent Strombolian eruption. Sample locations are shown in Fig. 1 and the relative details reported in Table 1. Details of the GSDs are available as Supplementary Material (Table S4).

711 344 *4.2 Total grain-size distributions*

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713 In this section, we describe the TGSDs estimated for the studied eruptions by using different 345 714 methods, such as the Voronoi tessellation method (Bonadonna and Houghton, 2005) or the 715 346 716 347 equivalent bulk grain-size distribution derived from massive PDC deposit (Macedonio et al., 1988; 717 348 Folch and Sulpizio, 2010), and the analytical parameterizations of the distributions (Costa et al., 718 ₇₁₉ 349 2016; 2017). The results give insights into the initial magma fragmentation corresponding to different eruptive styles at Somma-Vesuvius. Although our TGSD estimations are not based on a 720 350 721 351 large number of data in terms of spatial distribution, the dataset covers proximal, medial and distal 722 352 outcrops for all the studied eruptions. This is quite important as, irrespectively of the eruption style, 723 724 353 the lack of distal grain-size data can introduce a significant bias in the TGSD underestimating the 725 354 fines (e.g. PM_{10}) and, hence, preventing the assessment of the airborne ash, which can pose severe 726 355 hazards to the air traffic (Guffanti et al., 2005; Folch and Sulpizio, 2010; Sulpizio et al., 2014) and 727 728 356 public health (Tomašek et al., 2016; 2018).

729 357 As already mentioned, TGSDs are first estimated from field data analysis only (Fig. 6). They 730 indicate an overall bimodality pattern, except for the 1944 eruption. In particular, the Avellino field-358 731 732 359 derived TGSD peaks at 1 and 4 Φ , respectively for the coarse and fine sub-populations, the Pollena 733 360 TGSD shows modes at -1 and 6 Φ , and the 1906 TGSD has modes at 0 and 3 Φ . For comparison, 734 ₇₃₅ 361 the TGSD of the Pompeii Plinian eruption (from Macedonio et al., 2008) peaks at 1 and 5 Φ , in agreement with the TGSDs derived for the Avellino Plinian and Pollena sub-Plinian eruptions. For 736 362 737 363 comparison, the Pollena TGSD estimated assuming an equivalent bulk grain-size distribution 738 364 derived from massive PDC deposits by Folch and Sulpizio (2010) peaks at 1 and 4-5 Φ , 739 consistently with the estimations made for the Avellino and Pompeii TGSDs. Differently from the 740 365 741 366 other eruptions, the 1944 TGSD yields a unique mode at -2 Φ , more similar to the lower intensity 742 367 and lower magma viscosity eruptions (Costa et al., 2016). Considering the different eruptive styles 743 744 368 of the studied cases, the resulting field-based TGSDs indicate modes shifting towards the fines 745 369 when the eruption intensity increases, in agreement with the analysis performed in Costa et al. 746 370 (2016).747

748 371 The TGSDs estimated through the Voronoi tessellation method were obtained after a careful 749 investigation of the effects of the zero-line contour. In fact, TGSD assessment depends on several 750 372 751 373 factors, such as a suitable number of samples well dispersed along the main tephra dispersal (i.e. 752 374 proximal, medial, and distal areas), but also on the tephra edge defined as the zero-line (Bonadonna 753 and Houghton, 2005; Bonadonna et al., 2015). For optimizing the TGSD estimate, we used the 375 754 755 376 dispersals of the eruptions available in the literature (see Sect. 2) for constraining the tephra extents 756 377 for each studied eruption. Volentik et al. (2010) studied the uncertainty related to the position of the 757 378 zero-line, yielding uncertainties on the standard deviation of the modes and the fine ash contained 758 ₇₅₉ 379 within the TGSD. Nonetheless, Bonadonna et al. (2015) highlighted that these uncertainties are 760 380 much higher when tephra deposits are not sampled correctly, i.e. including sites up to distal area.

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Fig. 6: Field-based TGSDs (bars) for the Avellino, Pollena, 1906, and 1944 eruptions. Red lines show the bi-Gaussian distributions best fitting the field TGSDs, and the blue lines the bi-Weibull distributions. The dotted lines refer to the corresponding subpopulations of the relative distributions. Further details on the distributions in Sect. 3.2, and Tables 2, 3 and 4. The field-based TGSD for the Pompeii eruption is from Macedonio et al. (2008) and is used for comparison with the TGSD of the Avellino eruption. The second field-based TGSD for the Pollena eruption is derived from massive PDC deposits by Folch and Sulpizio (2010) and is used for comparison purpose with the Avellino and Pollena eruptions. Grey colours are consistent with Tables 3 and A (see Appendix).

Among tephra, very fine ash (e.g. PM_{10}) is released into the atmosphere where it can remain for days to weeks dispersing towards distal areas (Rose and Durant, 2009). Such fine material, which escapes to aggregation processes, is very difficult to sample due to the very long residence time in the atmosphere. It follows that PM₁₀ are typically under-sampled, biasing the field-derived TGSDs towards the fines and preventing the correct assessment of the airborne ash mass and the relative concentration (Poret et al., 2018a, 2018b), with implications for the assessment of hazards to the air traffic (e.g., Guffanti et al., 2005). In particular, the present study shows that Plinian eruptions (e.g. Avellino and Pompeii) may produce around 80 wt. % of ash with a PM₁₀ content of few percent (Table 3), which can have a strong impact on the air traffic safety producing extended areas with ash concentration above the threshold of 4 mg/m³ (Gouhier et al., 2019 and references therein) 819 397 delimiting the no-fly zones. It is worth noting that Gouhier et al. (2019) recently demonstrated that the more intense eruptions (i.e. Plinian) are the least efficient in transporting the airborne PM_{10} , due to early en masse fallout. This explains why we regularly observe ash in proximal and medial areas but also suggests that measured PM₁₀ fractions are the minimum amount to consider. A few studies 824 401 have attempted to assess such fraction at Etna (Sicily, Italy) integrating field and remote sensing

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829 data (i.e. satellite and/or X-band radar retrievals; Poret et al., 2018a, 2018b). Although PM₁₀ 402 830 831 403 fraction is negligible compared to the bulk tephra, it is critical for operational models (e.g. those 832 404 used by the Volcanic Ash Advisory Centers) when using the tephra dispersal models.

833 Considering the time occurrence of the studied eruptions, and the consequent absence of remote 405 834 sensing data, for trying to better capture the tails of the field-based TGSDs, i.e. fine and coarse, we 835 406 836 407 described the TGSDs by means of bi-Gaussian and bi-Weibull distributions, which allow 837 408 extrapolations. Overall, all the distributions best fitting the field TGSDs are estimated by assuming 838 839 409 two main tephra populations (i.e. a coarse and a fine) as described in Costa et al. (2016; 2017). 840 410 Indeed, Costa et al. (2016) show that bimodality of TGSDs is a common feature for several tephra ⁸⁴¹ 411 fallout deposits. This is also the case of this study, showing asymmetric and clear bimodal signature 842 ₈₄₃ 412 for all the TGSDs (Fig. 6), except for the 1944 eruption that, although asymmetric, has a more 844 413 unimodal pattern. However, the obtained TGSDs suggest that bimodality can be due to magma 845 414 heterogeneity, secondary fragmentation or phreatomagmatism (Jones and Russell, 2017). For better 846 415 classifying whether TGSDs are bimodal or unimodal, Costa et al. (2016) used a bimodality index 847 ₈₄₈ 416 (BI) for bi-Gaussian distributions as following:

$$BI = \sqrt{2} \frac{|\mu_1 - \mu_2|}{\sqrt{\sigma_1^2 + \sigma_2^2}} \sqrt{p(1-p)}$$

where the parameters μ_i and σ_i refer to modes and standard deviations of the Gaussian 853 418 ⁸⁵⁴ 419 distributions (Sect. 3.2). The best fitting parameters are reported in Table 2 together with the ₈₅₆ 420 associated BI values.

857 421 Table 2: Parameterization of the distributions in best fit of the field-based TGSDs for the Avellino, Pompeii, Pollena, 1906, and 858 422 1944 eruptions. p and (1-p) are, respectively, the coarse and fine sub-population weights, and μ_1 , μ_2 and σ_1 , σ_2 are the mean and 859 423 standard deviation of the two Gaussian distributions in Φ -units. q and (1-q) are, respectively, the coarse and fine sub-population 424 weights, and λ_1 , λ_2 and n_1 , n_2 are the scale and shape parameters of the two distributions, respectively. The bimodality is investigated 425 for the Gaussian distributions only through the BI (Costa et al., 2016), which is assumed bimodal for BI > 1.1. * TGSD is that used 861 426 from Macedonio et al. (2008) for comparing with the Avellino eruption. ** TGSD is that used by Folch and Sulpizio (2010).

002	bi-Gaussian						
003		Avellino	Pompeii *	Pollena	Pollena **	1906	1944
864	μ ₁ (Φ)	0.29 ± 0.07	0.14 ± 0.26	-0.78 ± 0.46	$\textbf{0.28} \pm \textbf{0.16}$	-1.52 ± 0.17	-2.74 ± 0.10
865	$\sigma_1(\Phi)$	1.16 ± 0.06	$\textbf{2.48} \pm \textbf{0.21}$	$\boldsymbol{2.60\pm0.38}$	$\textbf{2.86} \pm \textbf{0.13}$	1.64 ± 0.14	1.34 ± 0.08
866	$\mu_2(\mathbf{\Phi})$	4.12 ± 0.23	5.32 ± 0.25	$\textbf{4.99} \pm \textbf{0.17}$	$\textbf{4.87} \pm \textbf{0.16}$	$\textbf{3.08} \pm \textbf{0.11}$	$\textbf{0.08} \pm \textbf{0.24}$
867	$\sigma_2(\mathbf{\Phi})$	1.10 ± 0.19	$\textbf{1.04} \pm \textbf{0.20}$	$\boldsymbol{0.92 \pm 0.14}$	1.22 ± 0.13	1.10 ± 0.09	$\textbf{2.53} \pm \textbf{0.20}$
868	р	$\boldsymbol{0.77 \pm 0.02}$	$\boldsymbol{0.78 \pm 0.03}$	$\textbf{0.63} \pm \textbf{0.04}$	$\boldsymbol{0.79 \pm 0.02}$	$\textbf{0.53} \pm \textbf{0.03}$	$\textbf{0.48} \pm \textbf{0.03}$
869	BI	1.41	1.13	1.43	0.85	1.65	0.70
870	bi-Weibull						
871	λ_1 (in mm)	0.41 ± 0.04	$\textbf{0.43} \pm \textbf{0.07}$	$\boldsymbol{1.28\pm0.31}$	$\textbf{0.54} \pm \textbf{0.08}$	$\boldsymbol{1.27\pm0.12}$	$\textbf{4.82} \pm \textbf{0.28}$
872	n_1	$\textbf{0.65} \pm \textbf{0.03}$	$\textbf{0.38} \pm \textbf{0.01}$	$\textbf{0.42} \pm \textbf{0.03}$	$\textbf{0.37} \pm \textbf{0.01}$	$\textbf{0.40} \pm \textbf{0.01}$	$\textbf{0.95} \pm \textbf{0.05}$
873	λ_2 (in mm)	0.03 ± 0.01	$\textbf{0.02} \pm \textbf{0.01}$	$\textbf{0.02} \pm \textbf{0.01}$	$\textbf{0.02} \pm \textbf{0.01}$	$\textbf{0.07} \pm \textbf{0.01}$	$\textbf{0.84} \pm \textbf{0.07}$
073	n_2	1.16 ± 0.40	$\textbf{0.88} \pm \textbf{0.15}$	$\textbf{0.98} \pm \textbf{0.12}$	$\textbf{0.75} \pm \textbf{0.07}$	$\textbf{1.16} \pm \textbf{0.06}$	$\textbf{0.30} \pm \textbf{0.01}$
074 875	q	$\boldsymbol{0.86 \pm 0.04}$	$\textbf{0.74} \pm \textbf{0.04}$	0.56 ± 0.05	$\textbf{0.68} \pm \textbf{0.04}$	0.60 ± 0.02	$\textbf{0.32} \pm \textbf{0.02}$

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877 427 First of all, the results associated with the bimodal index (BI) reported in Table 2 tends to indicate bimodal distributions for all the TGSDs, except for that of the Pollena eruption estimated from 878 428 879 429 Folch and Sulpizio (2010) and the 1944 distribution. Indeed, their values are below 1.1, suggesting 880 a more unimodal distribution, although these distributions are made by coarse and fine populations, 430 881 882 431 which are close enough for showing a unimodal-like shape of the distributions (Fig. 6).

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Considering that TGSD is needed as input parameter for tephra dispersal models, typically in the
form of discrete size bins, we report the TGSD bins obtained from the field measurements analysis
(i.e. Field TGSD) and the corresponding bi-Gaussian and bi-Weibull distributions for the studied
eruptions in the Appendix (Tables A1-6). Moreover, we discuss below the magma fragmentation
features inferred for each eruption. For the sake of simplicity, Table 3 reports the mass fractions
associated with each grain-size class (i.e. bomb, lapilli, coarse, and fine ash).

896 Putting together the field-based TGSDs and the relative analytical distributions (i.e. bi-Gaussian 438 897 and bi-Weibull), results for the Avellino eruption suggest a first mode between 0 and 1 Φ and a 898 439 899 440 second mode at 4 Φ , respectively for the coarse and fine sub-populations (Fig. 6; Table A1). The 900 441 Pollena TGSD shows a first mode from -2 to -1 Φ and a second mode at 5-6 Φ . As described in 901 902 442 Sect. 2, the Avellino and Pollena eruptions have similar eruptive trends, even if they are classified 903 443 as Plinian and sub-Plinian eruptions, respectively. Comparing the relative sub-populations ⁹⁰⁴ 444 displayed in Fig. 6, the Pollena TGSD indicates a tephra deposit relatively coarser than for 905 ₉₀₆ 445 Avellino, with a greater production of lapilli (~30 and ~18 wt. % respectively; Tables A1 and A2). In contrast, the Avellino eruption produced substantially more ash than the Pollena one (~80 against 907 446 908 447 ~60 wt. % of ash respectively; Tables A1 and A3), being an indicator of the efficiency of the 909 448 magma fragmentation. Going further in detail, the Avellino eruption produced more coarse ash with 910 respect to Pollena (~70 vs. ~35 wt. % respectively), whereas the Pollena eruption has more fine ash 911 449 912 450 (~8 vs. ~30 wt. %). Furthermore, the PM_{10} content is greater for the Pollena eruption compared to ⁹¹³ 451 Avellino (~4 and ~1 wt. % respectively; Tables A1 and A3), indicating either a more efficient 914 . 915 452 magma fragmentation for Pollena, although the eruption showed very unstable eruptive conditions, 916 453 or a more efficient transport towards distal region, as suggested by Gouhier et al. (2019). It is worth 917 454 noting that the magmatic phase of the Avellino eruption was accompanied by an energy drop 918 455 affecting magma fragmentation, representing the phreatomagmatic phase (Sulpizio et al., 2008; 919 ₉₂₀ 456 2010b) with a lower fraction of fine ash compare to the Pollena eruption. Sulpizio et al. (2005) 921 457 explained this as due to magma fragmentation efficiency but also mentioned the occurrence of an 922 458 extensive magma-water interaction, which occurred during the final phase, carrying out a strong 923 459 control on the eruption dynamics and increasing the fragmentation of magma during the Pollena 924 925 460 eruption.

926 461 Going further in the comparative analysis, we compared the Avellino field-derived TGSD with the 927 928 462 one of the Pompeii eruption, being both Plinian events. For these purposes, we used the TGSD estimations reported by Macedonio et al. (1988; 2008) for the Pompeii eruption. Macedonio et al. 929 463 930 464 (1988; see Fig. 2b therein) estimated the TGSD from an individual GSD obtained from an outcrop 931 of PDC deposits representative of the collapse of the eruptive column. Concerning the fine ash 465 932 933 466 content, they considered all the bin fractions corresponding to $\Phi \ge 5$ all together as fine residual at 934 467 $\Phi = 5$. It follows that we consider only the coarse mode that peaks at 1 Φ , being consistent with the 935 Avellino results. Regarding the class fractions, we can see that this TGSD shows a substantial 468 936 937 469 enrichment in lapilli (~37 wt. % against ~18 wt. % respectively; Table 3), and thus, a depletion in 938 470 ash compared to the Avellino eruption (~63 wt. % against ~82 wt. % respectively). Moreover, it ⁹³⁹ 471 also shows a slight enrichment in fine ash (~14 wt. % against ~10 wt. % respectively). Then, 940 ₉₄₁ 472 Macedonio et al. (2008) reported the bulk Pompeii TGSD that they assumed representative of the Plinian/Sub-Plinian granulometry at Somma-Vesuvius. We also reconstructed such field-based 942 473

⁹⁴⁷ 474 TGSD through a bi-Gaussian and bi-Weibull distribution and they are displayed in Fig. 6 for 948 comparing them with the Avellino TGSD. It shows a mode at 0-1 Φ for the coarse population, and 949 475 950 476 at 5 Φ for the fine population (Tables A1-2). Although the paucity of field data implies large 951 477 uncertainties on the TGSD assessment, the relative TGSDs indicate comparable values for lapilli 952 478 and ash (Table 3), suggesting acceptable results. Looking at the class fractions, the Pompeii TGSD 953 from Macedonio et al. (2008) shows comparable values with respect to the other TGSDs, with ~24 954 479 955 480 and ~76 wt. % of lapilli and ash, respectively. Among ash, the TGSD indicates ~52 wt. %, 24 wt. 956 481 %, and ~6 wt. % of coarse and fine ash, and PM_{10} . It follows that all the three estimates for the 957 958 482 Plinian events (i.e. Avellino and Pompeii) are in agreement with a dominancy of ash between 60 959 483 and 80 wt. % of the magma fragmentation, being consistent with Rose and Durant (2009) who ⁹⁶⁰ 484 discussed how silicic eruptions can contain substantial fractions of ash. 961

962 485 Similarly to the previous paragraph, we used the TGSD of the Pollena eruption used by Folch and ⁹⁶³ 486 Sulpizio (2010) for a comparison with our TGSD estimates (see Fig. 6). They obtained the TGSD 964 ₉₆₅ 487 on the basis of an individual GSD obtained from an outcrop of PDC deposits representative of the collapse of the eruptive column. We also best-fitted their field-based TGSD through the bi-966 488 967 489 Gaussian and bi-Weibull distributions. The TGSD peaks at 0-1 Φ and 4 Φ for the coarse and fine 968 490 populations respectively. This is slightly different from our estimate for the Pollena eruption (see 969 Tables A3-4), which can be attributed to a different method for assessing the TGSD. In fact, based 970 491 971 492 on our analysis of the field samples, we obtained a TGSD composed of two more marked grain size ⁹⁷² 493 populations than for the TGSD of Folch and Sulpizio (2010). In particular, our TGSD suggest a 973 coarser proximal deposit with ~31 wt. % of lapilli instead of ~25 wt. % by Folch and Sulpizio 494 974 975 495 (2010). Regarding the class fractions (Table 3), we can see that Folch and Sulpizio (2010) obtained 976 496 ~75 wt. % of ash, whereas our TGSD indicates ~69 wt. %. Furthermore, they suggest ~52 wt. %, 23 977 497 wt. %, and ~5 wt. % of coarse and fine ash, and PM_{10} , while we have ~37 wt. %, 33 wt. %, and ~3 978 ₉₇₉ 498 wt. %, respectively. These results are comparable showing an agreement in favour of saying that 980 499 during the Pollena eruption magma fragmentation produced around 30 wt. % of lapilli and 70 wt. % 981 500 of ash, with ~45 wt. % of coarse ash, ~30 wt. % of fine ash, and ~4 wt. % of PM₁₀. In addition, 982 501 these results are very similar to those of the Plinian eruptions and reinforce the similarity between 983 984 502 the Plinian and sub-Plinian eruptive styles.

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Table 3: Fractions of the different classes used in this study: bombs ($\Phi \le -6$), lapilli ($-5 \le \Phi \le -1$), and ash ($0 \le \Phi$). We further distinguish between coarse ($4 \le \Phi \le 0$) and fine ash ($\Phi \le 5$) as described in Folch (2012). We also reported the PM₁₀ fraction (diameter below 10 µm) as in Poret et al. (2018b). The fractions are expressed in weight percentage (wt. %) and refer to the field-TGSDs, bi-Gaussian, and bi-Weibull distributions for the Avellino, Pollena, 1906, and 1944 Somma-Vesuvius eruptions. Colours are consistent with Tables A (see Appendix) and Fig. 6. * Pompeii data are extracted from Macedonio et al. (2008) for comparing with Plinian and sub-Plinian eruptions.

	Class	Field-TGSD	bi-Gaussian	bi-Weibull
	Bombs	0.00	0.00	0.00
	Lapilli	17.62	18.70	19.71
00	Ash	82.38	81.29	80.28
<i>i</i> elli	Coarse ash	72.65	73.14	72.15
A 1	Fine ash	9.73	8.15	8.13
	PM_{10}	0.35	0.29	0.81
	Total	100	100	100
	Bombs	0.00	0.59	0.00
	Lapilli	23.98	30.29	24.80
*	Ash	78.28	69.12	75.20
npe	Coarse ash	52.11	48.77	52.17
Poi	Fine ash	24.17	20.35	23.03
	PM_{10}	6.05	2.95	5.21
	Total	100	100	100
	Bombs	0.00	1.31	0.12
	Lapilli	30.58	32.53	36.10
na	Ash	69.44	66.17	63.79
olle	Coarse ash	36.71	38.48	35.12
2	Fine ash	32.73	27.69	28.67
	PM_{10}	3.26	1.71	4.58
	Total	100	100	100
	Bombs	0.00	0.99	0.01
	Lapilli	24.53	29.34	26.89
**	Ash	75.12	69.67	73.09
llen	Coarse ash	51.84	50.80	53.12
Po	Fine ash	23.28	18.87	19.97
	PM_{10}	5.10	2.93	4.08
	Total	100	100	100
	Bombs	0.00	0.31	0.19
	Lapilli	30.78	38.73	38.10
9	Ash	69.22	60.95	61.70
190	Coarse ash	55.78	56.72	56.48
	Fine ash	13.44	4.23	5.22
	PM_{10}	2.07	0.03	0.40
	Total	100	100	100
	Bombs	0.00	1.21	0.42
	Lapilli	58.73	65.92	65.77
4	Ash	41.28	32.86	33.80
194	Coarse ash	35.66	30.83	31.54
	Fine ash	5.62	2.03	2.26
	PM_{10}	0.02	0.27	0.52
	Total	100	100	100

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1064 1065 1066 511 Regarding the Violent Strombolian eruptions at Somma-Vesuvius, the TGSD reconstructed for the 1906 eruption has a first mode from -2 to 0 Φ for the coarse sub-population, and a second mode at 3 1067512 1068513 Φ for the fine sub-population (Table 3; Fig. 6). The 1944 TGSD presents significant differences 1069 1070 514 with respect to the 1906 one, showing a unimodal pattern with a main mode between -3 and -2 Φ . 1071515 Indeed, the second mode is not clearly visible from the Field TGSD, characterizing the fine sub-1072516 population and peaking between -1 and 0 Φ (respectively for the bi-Weibull and bi-Gaussian 1073517 1074 1075518 distributions), partially overlapping the coarse sub-population (see Fig. 6). Such discrepancy between the 1906 and 1944 TGSDs can be interpreted as due to the different processes controlling 1076519 magma fragmentation, such as the higher intensity and the major phreatomagmatic phase of the 1077520 1906 eruption (Costa et al., 2016). In fact, these results, together with the features of the Pollena 1078 1079 521 TGSD, support the importance of the phreatomagmatic phase in controlling magma fragmentation 1080522 (Sulpizio et al., 2010b). As described in Sect. 2.3, the 1906 and 1944 eruptions are similar in terms 1081523 of eruptive style. Comparing the class fractions, the 1906 TGSD is substantially depleted in lapilli ¹⁰⁸²524 ¹⁰⁸³ 1084</sub>525 than the 1944 one (~31 and ~59 wt. % respectively; Table 3), but enriched in ash (respectively ~69 and ~41 wt. %; Table 3). Accordingly, the literature (Arrighi et al., 2001) reports that the 1944 event produced a large quantity of lapilli. Another feature reported for the 1944 eruption concerns 1085526 1086527 the production of ash aggregates up to centimetric size (Arrighi et al., 2001). Although aggregation 1087₅₂₈ 1088 1089⁵²⁹ implies a premature tephra fallout (Durant et al., 2009; Mastin et al., 2016; Poret et al., 2018c), it also depletes the TGSD in fines (Poret et al., 2017), affecting the grain-size distribution towards the 1090530 fine ash. This also depends on the sampling distance from the source as highlighted by Spanu et al. 1091531 (2016). Comparing coarse and fine ash, the results indicate a greater production for the 1906 1092 1093 532 compared to the 1944 eruption (respectively ~56 against ~36 wt. % for the coarse ash, and ~13 against ~6 wt. % for the fine ash; Table 3). Furthermore, the PM_{10} fractions yield ~2 wt. % and <1 1094533 1095534 wt. % for the 1906 and 1944 eruptions, respectively.

1096 1097535 Summarizing the TGSD analyses, the results allow identifying distinctive grain-size features for the 1098536 different eruptive styles at Somma-Vesuvius, although the paucity of field data prevents assuming 1099₅₃₇ 1100 1101⁵³⁸ the reconstructed TGSDs as fully representative of the initial magma fragmentation conditions. Indeed, results generally indicate that increasing in intensity (i.e. from Violent Strombolian to 1102539 Plinian eruptions) tends to move the main modes of the TGSDs towards the fines (Fig. 6 and Tables 1103540 A). Such feature was also reported by Costa et al. (2016), who proposed a model for estimating the ¹¹⁰⁴541 TGSD through the bulk magma viscosity and column height. They observed the mode shifting 1106542 towards the fines when increasing the magma viscosity and intensity values. In particular, the 1107543 Plinian eruptions (e.g. Avellino and Pompeii at Somma-Vesuvius) appear to be the richest in ash 1108544 with up to ~82 wt. % (Table 3). In addition, the Pollena sub-Plinian eruption with ~70 wt. % of ash ¹¹⁰⁹ 1110⁵45 (PM₁₀ of ~4 wt. %) and the 1906 Violent Strombolian eruption with ~69 wt. % of ash (PM₁₀ of ~2 wt. %) show exceptional magma fragmentation efficiency in contrast with the Avellino, Pompeii, 1111546 1112547 and 1944 eruptions. 1113

¹¹¹⁴548 **5** Conclusions

This study presents grain-size analyses obtained from several tephra samples associated with four reference eruptions of Somma-Vesuvius, covering different eruptive styles (from Violent Strombolian to Plinian), aimed to assess the relative TGSD and the impact of magma fragmentation

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1123 ¹¹²⁴552 on the eruptive styles. Chronologically, we focus on the Avellino (3900 yr BP) and the Pompeii 1126553 (A.D. 79) Plinian eruptions, the Pollena sub-Plinian eruption (A.D. 472), and the 1906 and 1944 1127554 Violent Strombolian eruptions. Previous estimations of the Pompeii and Pollena eruptions were 1128555 used for comparison purposes in terms of magma fragmentation for a given eruptive style. ¹¹²⁹ 1130⁵⁵⁶ Individual field-based grain-size analyses were integrated using the Voronoi tessellation method for 1131557 assessing the TGSD relative to each eruption. Besides the estimation of the field-derived TGSDs, 1132558 we parameterized the TGSDs using the analytical bi-Gaussian and bi-Weibull distributions. By ¹¹³³559 comparing the TGSDs associated with the different eruptive styles, our results indicate that 1134 1135⁵⁶⁰ increasing the eruption intensity, i.e. going from Violent Strombolian to Plinian eruptive style, and 1136561 the efficiency of magma-water interaction, i.e. from magmatic to phreatomagmatic eruptions, 1137562 TGSD modes move towards the fines, enhancing magma fragmentation. This study brings together ¹¹³⁸563 similar conclusions in terms of magma fragmentation stated in the literature, reinforcing their 1140564 findings and reopening the interest of studying the fragmentation from field data but not limited to. 1141565 We believe this study will serve further works focussing on characterizing the tephra distribution 1142566 produced by volcanic eruptions worldwide from Violent Strombolian to Sub-Plinian and Plinian ¹¹⁴³ 1144⁵67 styles. In particular, the main findings of this study can be used for numerically reconstructing past eruptions or forecasting similar eruptive scenarios at Somma-Vesuvius, and assessing tephra 1145568 1146569 loading and/or airborne ash mass from the source towards distal regions. 1147

1148570 Acknowledgements

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¹¹⁸³577 **Appendix**

1185578Table A1: Field-derived TGSD together with the corresponding bi-Gaussian and bi-Weibull distributions for the Avellino Plinian.1186579TGSDs are expressed in weight percentage (wt. %) and displayed in Fig. 6. The related grain-size class fractions are reported in
Table 3. Colours are consistent with Fig. 6 and Table 3.

Diameter (Ф)	Field TGSD	bi-Gaussian	bi-Weibull
 -6	0.00	0.00	0.00
-5	0.35	0.00	0.00
-4	1.61	0.03	0.00
-3	3.31	0.49	0.26
-2	5.09	3.83	4.07
-1	7.26	14.35	15.38
0	18.00	25.72	23.69
1	27.66	22.17	20.60
2	13.53	10.31	12.46
3	6.13	6.65	7.42
4	7.33	8.29	7.98
5	6.31	5.95	5.28
6	3.07	1.91	2.04
7	0.35	0.27	0.60
8	0.00	0.02	0.16
9	0.00	0.00	0.04
10	0.00	0.00	0.01

Table A2: Field-derived TGSD from Macedonio et al. (2008) together with the corresponding bi-Gaussian and bi-Weibull distributions for the Pompeii Plinian eruption. TGSDs are expressed in weight percentage (wt. %) and displayed in Fig. 6. The related grain-size class fractions are reported in Table 3. Colours are consistent with Fig. 6 and Table 3.

Diameter (Φ)	Field TGSD	bi-Gaussian	bi-Weibull
-6	0.00	0.59	0.00
-5	1.00	1.47	0.10
-4	3.98	3.13	0.80
-3	7.00	5.65	3.32
-2	6.00	8.69	7.97
-1	6.01	11.35	12.61
0	12.03	12.59	14.43
1	17.03	11.88	12.88
2	10.04	9.58	9.49
3	6.01	7.19	6.71
4	7.00	7.53	8.66
5	9.06	9.87	10.54
6	9.07	7.53	7.28
7	5.03	2.53	3.39
8	1.02	0.38	1.27
9	0.00	0.04	0.42
10	0.00	0.00	0.13

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1221585**Table A3**: Field-derived TGSD together with the corresponding bi-Gaussian and bi-Weibull distributions for the Pollena sub-Plinian
eruption. TGSDs are expressed in weight percentage (wt. %) and displayed in Fig. 6. The related grain-size class fractions are
reported in Table 3. Colours are consistent with Fig. 6 and Table 3.

Diameter (Φ)	Field TGSD	bi-Gaussian	bi-Weibull
-6	0.00	1.31	0.12
-5	0.38	2.63	1.04
-4	2.08	4.56	3.95
-3	7.67	6.81	8.38
-2	9.97	8.77	11.45
-1	10.48	9.76	11.28
0	7.32	9.36	8.70
1	5.18	7.74	5.59
2	13.57	5.61	3.15
3	1.15	4.96	4.03
4	9.49	10.81	13.65
5	13.65	16.86	15.55
6	15.82	9.12	8.54
7	3.26	1.59	3.22
8	0.00	0.11	1.00
9	0.00	0.01	0.28
10	0.00	0.00	0.08

Table A4: Field-derived TGSD from Folch and Sulpizio (2010) together with the corresponding bi-Gaussian and bi-Weibull distributions for the Pollena sub-Plinian eruption. TGSDs are expressed in weight percentage (wt. %) and displayed in Fig. 6. The related grain-size class fractions are reported in Table 3. Colours are consistent with Fig. 6 and Table 3.

Diameter (Φ)	Field TGSD	bi-Gaussian	bi-Weibull
-6	0.00	0.99	0.01
-5	0.00	2.00	0.20
-4	4.14	3.60	1.27
-3	5.70	5.72	4.28
-2	6.92	8.03	8.79
-1	7.76	9.99	12.35
0	10.36	11.00	12.92
1	12.31	10.76	10.78
2	10.59	9.66	8.17
3	8.14	9.18	9.28
4	10.44	10.20	11.97
5	10.33	9.86	10.09
6	7.86	6.08	5.80
7	5.10	2.22	2.60
8	0.00	0.54	1.00
9	0.00	0.13	0.36
10	0.00	0.04	0.12

1260⁵⁹⁰ 1261⁵⁹¹ Table A5: Field-derived TGSD together with the corresponding bi-Gaussian and bi-Weibull distributions for the 1906 Violent Strombolian eruption. TGSDs are expressed in weight percentage (wt. %) and displayed in Fig. 6. The related grain-size class fractions are reported in Table 3. Colours are consistent with Fig. 6 and Table 3.

D	iameter (Φ)	Field TGSD	bi-Gaussian	bi-Weibull
	-6	0.00	0.31	0.19
	-5	0.00	1.35	1.30
	-4	2.90	4.11	4.42
	-3	6.41	8.59	8.85
	-2	9.91	12.38	11.84
	-1	11.56	12.30	11.69
	0	12.44	8.72	9.15
	1	6.53	6.78	6.32
	2	5.17	11.81	12.01
	3	18.41	17.34	18.40
	4	13.23	12.07	10.60
	5	7.67	3.70	3.74
	6	3.70	0.50	1.08
	7	2.07	0.03	0.29
	8	0.00	0.00	0.08
	9	0.00	0.00	0.02
	10	0.00	0.00	0.01

Table A6: Field-derived TGSD together with the corresponding bi-Gaussian and bi-Weibull distributions for the 1944 Violent Strombolian eruption. TGSDs are expressed in weight percentage (wt. %) and displayed in Fig. 6. The related grain-size class fractions are reported in Table 3. Colours are consistent with Fig. 6 and Table 3.

Diameter (Φ)	Field TGSD	bi-Gaussian	bi-Weibull
-6	0.00	1.21	0.42
-5	1.20	4.57	3.14
-4	6.96	11.48	12.88
-3	17.20	18.00	18.68
-2	17.66	18.18	16.98
-1	15.71	13.69	14.09
0	13.36	10.00	11.37
1	8.21	7.98	8.54
2	7.54	6.18	5.85
3	3.26	4.21	3.66
4	3.29	2.46	2.12
5	4.03	1.23	1.15
6	1.57	0.53	0.59
7	0.02	0.19	0.29
8	0.00	0.06	0.14
9	0.00	0.02	0.06
10	0.00	0.00	0.03

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