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## Estimating eruptive parameters and related uncertainties for pyroclastic density currents deposits: worked examples from Somma-Vesuvius (Italy)

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<b>Abstract:</b>	<p>The quantification of the maximum runout, invaded area, volume and total grain-size distribution (TGSD) of pyroclastic density currents (PDC) is a critically important task because such parameters represent the needed input quantities for physical modeling and for hazard assessment of PDCs. In this work, new and well-established methods for the quantification of these parameters are applied to a large stratigraphic dataset of three PDC units from two eruptions of Somma-Vesuvius (the AD 79 Pompeii and the AD 472 Pollena eruptions), representative of a large spectrum of transport and depositional processes. Maximum runout and invaded area are defined on the basis of the available volcanological and topographical constraints. The related uncertainties are evaluated with an expert judgement procedure, which considered the different sectors of the volcano separately. Quite large uncertainty estimates of dispersal area (20-40%) may have important implications in terms of hazard assessment. The testing of different methods for estimating the volume (and mass) of a PDC deposit suggests that integration, over the invaded area, of thickness (and deposit density) data using the triangulated irregular network method can minimize and localize data extrapolation. Such calculations, however, bear an intrinsic additional uncertainty (at least 10% of the total PDC deposit) related to loss or new formation of fine material during transport (at least 10% of the total PDC deposit). Different interpolation methods for TGSD produce multimodal distributions, likely reflecting the different response of each grain size class to transport and deposition processes. These data, when integrated with information on the related co-ignimbrite deposits, can give a more accurate picture of the pyroclastic mixture feeding the current.</p>	
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<b>Author Comments:</b>	<p>Dear publication office,</p> <p>as I have written to Fran van wyk de vries today, I am not able to link my current BV account to my ORCID account due to a previous BV account of mine with another email (not active anymore) which is linked to my ORCID account. If it is possible to delete my old account and merge the information from the old account to my current account that would be great. If not, could you please delete the old account?</p> <p>Thanks a lot for your help Best Regards</p> <p>Alessandro Tadini</p>

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1 **Estimating eruptive parameters and related uncertainties for pyroclastic density**  
2 **currents deposits: worked examples from Somma-Vesuvius (Italy)**

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## 37 **Availability of data and material**

38 The Online Resources presented in this study could be found also in a repository in the Figshare community with the  
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40

## 41 **Abstract**

42 The quantification of the maximum runout, invaded area, volume and total grain-size distribution (TGSD) of  
43 pyroclastic density currents (PDC) is a critically important task because such parameters represent the needed input  
44 quantities for physical modeling and for hazard assessment of PDCs. In this work, new and well-established methods for the  
45 quantification of these parameters are applied to a large stratigraphic dataset of three PDC units from two eruptions of  
46 Somma-Vesuvius (the AD 79 Pompeii and the AD 472 Pollena eruptions), representative of a large spectrum of transport  
47 and depositional processes. Maximum runout and invaded area are defined on the basis of the available volcanological and  
48 topographical constraints. The related uncertainties are evaluated with an expert judgement procedure, which considered the  
49 different sectors of the volcano separately. Quite large uncertainty estimates of dispersal area (20-40%) may have important  
50 implications in terms of hazard assessment. The testing of different methods for estimating the volume (and mass) of a PDC  
51 deposit suggests that integration, over the invaded area, of thickness (and deposit density) data using the triangulated  
52 irregular network method can minimize and localize data extrapolation. Such calculations, however, bear an intrinsic  
53 additional uncertainty (at least 10% of the total PDC deposit) related to loss or new formation of fine material during  
54 transport (at least 10% of the total PDC deposit). Different interpolation methods for TGSD produce multimodal  
55 distributions, likely reflecting the different response of each grain size class to transport and deposition processes. These  
56 data, when integrated with information on the related co-ignimbrite deposits, can give a more accurate picture of the  
57 pyroclastic mixture feeding the current.

58

59

## 60 **Keywords**

61 Pyroclastic Density Currents; Somma-Vesuvius; maximum runout; volume; total grain size distribution;  
62 uncertainty quantification

## 63 1. Introduction

64 The starting point for the assessment of volcanic hazard is an accurate reconstruction of the eruptive history of a  
65 volcano, which in turn relies upon the availability of detailed field data that provide physical characterization of the possible  
66 outcomes of a future eruption (Neri et al. 2008). While methods for estimating eruption source parameters related to tephra  
67 fallout are clearly defined and numerical modeling has been generally developed based on these data (Biass et al. 2014),  
68 measurements on pyroclastic density current (PDC – called also pyroclastic currents) deposits have been used only recently  
69 to constrain the related numerical models (e.g., Esposti Ongaro et al. 2012, 2016; Spiller et al. 2014). Some of the most  
70 important parameters that need to be evaluated to constrain PDC-related hazards are: a) maximum runout distance, b) extent  
71 of invaded area, c) total volume and d) total grain size distribution (TGSD) of the flow mixture. In parallel,  
72 sedimentological investigations on the deposits aimed at defining the main transport and depositional processes of the  
73 parental current are fundamental for the definition of the assumptions that have to be made in the physical modeling, and  
74 hence of the models to be used (Patra et al. 2018, 2020). Despite several attempts to estimate these parameters for PDCs, the  
75 latter are known to be affected by several sources of epistemic uncertainty (see Bevilacqua et al. 2017; Rutarindwa et al.  
76 2019). Presently the volcanological community lacks a standardized approach for estimating PDC-related parameters from  
77 their deposits. This is primarily due to the complexity of the depositional processes, which are strongly controlled by the  
78 interaction of the current with the underlying topography and by the mechanics of particle transport in the different regions  
79 of the current: such complexity prevents the description of the thickness or grain-size of PDC deposits simply as a function  
80 of the distance from the vent (Druitt 1998; Branney and Kokelaar 2002).

81 Here we quantify key parameters for a range of PDC deposits at Somma-Vesuvius volcano that can be used as  
82 input data for numerical simulations for volcanic hazard assessment, and to provide extensive uncertainty quantification.  
83 The different methodologies presented and discussed here provide a blueprint for the development of standard procedures  
84 for the assessment of these important parameters and the related uncertainty. We present new and revised data from PDC  
85 deposits from two different eruptions at Somma-Vesuvius (Fig. 1): i) the AD 79 Pompeii Plinian eruption and ii) the AD  
86 472 Pollena sub-Plinian eruption. These PDC deposits resulted from different transport and deposition conditions, allowing  
87 us to test different methods of estimation over diverse natural conditions. Therefore, for each of the previously listed  
88 parameters, different methods were refined and used for their quantification, results obtained for the same parameter from  
89 different methods were compared and discussed, and an average value among the methods is provided for each parameter.

90

## 91 2. Types of pyroclastic density currents at Somma-Vesuvius

92 We consider two end-member types of PDCs, common during Plinian and sub-Plinian eruptions (Cioni et al. 2004;  
93 Cioni et al. 2008):

94 i) dilute PDCs, where turbulence is the main supporting mechanism (Branney and Kokelaar 2002). Deposits  
95 from this type of PDC are here represented by the EU3pf (Fig. 2a) and EU4b (Fig. 2b) PDC units from the  
96 AD 79 Pompeii eruption (Cioni et al. 2004; Gurioli et al. 2007). They are composed of tuff and fine lapilli  
97 tuff, and characterized by a progressive, although irregular, variation of grain size, texture and thickness  
98 with distance from source and by the presence of traction structures such as planar and cross beds with  
99 internal coarse-tail grading.

100 ii) dense PDCs, where transport of particles is dominated by collisional momentum transfer between grains  
101 (Branney and Kokelaar 2002). Deposits of this type are represented by two PDC lobes (i.e. the “Cupa  
102 Olivella” and “Cupa Fontana”) belonging to the  $F_g$  unit of the AD 472 Pollena eruption (Sulpizio et al.  
103 2005; Sulpizio et al. 2007). They are characterized by massive deposits up to 12 meters thick that are  
104 mainly confined to deeper paleovalleys, and that exhibit no variation in grainsize with distance (Fig. 2c).  
105

#### 106 2.1 AD 79 deposits

107 Cioni et al. (1992) divided the AD 79 eruptive sequence into 8 main eruptive units (EU1-EU8) and some minor  
108 sub-units. Three main phases of the eruption (opening phase, Plinian phase and phreatomagmatic phase) were distinguished  
109 and PDC deposits are mainly related to the last two phases (Cioni et al. 1992).

110 The PDC deposits of the EU3pf unit (Fig. 2a) are considered to be derived from the final collapse of the Plinian  
111 column (Cioni et al. 2004). They are typically about one meter thick, are radially dispersed up to 10 km from vent, and have  
112 complex vertical and lateral facies variability (Gurioli 1999; Gurioli et al. 1999) that can be ascribed to local variation in  
113 turbulence and particle concentration and to the stratification of the current. Median clast size tends to diminish gradually  
114 from proximal to distal locations, and the coarsest deposits (generally present as tuff breccia lenses in the EU3pf sequence)  
115 are located within paleodepressions. Gurioli et al. (1999) noted that: i) in the southern part of the Somma-Vesuvius area (see  
116 Fig. 3) the relatively smooth paleo-topography exerted only localized control on the overall deposition of the PDC; ii) in the  
117 eastern sector of Somma-Vesuvius, where the current climbed over the remnants of the old Mount Somma scarp, the  
118 paleotopography induced a general increase of the current turbulence and velocity and more efficient air ingestion; iii) in the  
119 western sector of Somma-Vesuvius (Fig. 3), the presence of a breach in the caldera wall and a major break in slope in the  
120 area of Piano delle Ginestre (see Fig. 3), possibly increased deposition from the PDC, producing a large depositional fan  
121 with thicknesses up to several meters toward sea-facing sectors (e.g., in Ercolano, Fig. 1); iv) in the northern sector of  
122 Somma-Vesuvius (see Fig. 3), the deeply eroded paleotopography (with many valleys and steep slopes) favored the  
123 development within the whole current of a fast-moving, dense basal underflow confined in the main valleys, with a slower  
124 and more dilute portion travelling along morphological highs.

125 The AD 79 EU4 unit (Fig. 2b) resulted from a short-lived column that emplaced three distinct layers (Cioni et al.  
126 1992): a thin, basal fallout layer (“EU4a”, Fig. 2b); a PDC deposit which represents on average 60-90% of the total EU4  
127 thickness, interpreted as the result of column collapse (“EU4b”, Fig. 2b); a co-ignimbrite ash fall layers relating to EU4b  
128 (“EU4c”, Fig. 2b). The runout of the EU4b PDC is one of the greatest observed for PDCs at Somma-Vesuvius (20 km;  
129 Gurioli et al. 2010) and it reached the area presently occupied by the town of Nocera Inferiore (Fig. 1). This unit has been  
130 extensively studied by Gurioli (1999) and Gurioli et al. (2005), who highlighted that: i) EU4b shows clear vertical grain size  
131 and textural variations, and varies from cross bedded, fine lapilli to coarse ash laminae at the base to a massive, fine ash-  
132 bearing, poorly sorted, matrix-supported bed at top; ii) the extended erosion of the pumice-bearing layer of the underlying  
133 EU4a is an evidence of the high shear rate exerted by the EU4b whose deposit can be interpreted as derived from a short-  
134 lived density stratified PDC.

135

136

137

138 *2.1 AD 472 deposits*

139 The AD 472 Pollena eruption was classified by Cioni et al. (2008) as a sub-Plinian type I event, distinguished from  
140 a sub-Plinian type II event based on size and magnitude (both higher for the sub-Plinian type I) and on the dispersal of PDC  
141 deposits (within 2/3 km and 8/9 km from the vent for the sub-Plinian type II and type I, respectively). The AD 472 Pollena  
142 eruption was characterized by volumetrically important PDCs (0.15 km<sup>3</sup>; Sulpizio et al. 2007) and by a sustained phase  
143 which, unlike the Plinian case, is interpreted to have been dominated by an instability in magma discharge. Sulpizio et al.  
144 (2007) subdivided the eruption into three main eruptive phases according to inferred changes in the eruptive processes  
145 and/or changes in melt composition. The PDC deposits are associated with the last two eruptive phases, including the PDC  
146 deposits of unit F<sub>g</sub> (Sulpizio et al. 2005), whose physical parameters have been here calculated. During the eruption, the  
147 formation of PDC might have been related to partial or total collapses of the convective column responsible for the  
148 deposition of the two preceding fallout units (L8 and L9; Sulpizio et al. 2005). Deposition of the F<sub>g</sub> unit of the AD 472  
149 Pollena eruption (Fig. 2c) was generally strongly controlled by topography, with massive to stratified, lapilli-bearing, ash-  
150 and lithic-rich deposits and only minor, cross-laminated to dune-bedded deposits. The thickness varies from a few tens of  
151 cm up to 7 m. Lithofacies in F<sub>g</sub> units consist of massive, valley-ponded lapilli tuff with few examples of crudely stratified  
152 ash deposits at the bottom of this lithofacies (Sulpizio et al. 2007). Sedimentological features suggest that deposition  
153 occurred from a highly concentrated, granular to fluid-escape dominated underflow at the base of a thick, short-lived,  
154 rapidly depletive current (Sulpizio et al. 2007).

155

156 **3. Datasets**

157 Field data for each of the studied PDC deposits are here used for extracting quantitative physical parameters. We  
158 focus on the quantitative assessment of the following parameters and of their inherent uncertainties: (1) maximum runout  
159 distance; (2) flow invaded area; (3) volume of the deposit; (4) total grain size distribution of the PDC.

160 Because a standardized protocol is not available for the quantification of these parameters for PDC deposits, we  
161 compare results obtained through the application of different methods. Samples and measurements refer to a total of 243  
162 stratigraphic sections (Fig. 3), either partially unpublished or taken from published studies (Cioni et al. 1992; Gurioli 1999;  
163 Gurioli et al. 1999; Tadini et al. 2017b). Data on stratigraphic sections, samples and density measurements of the deposits  
164 are available in the Supplementary Material section (Online Resources 1, 2, 3 and 4) and shown in Figure 3 and Online  
165 Resource 5. The three PDC deposits, which vary terms of transport and depositional mechanics, dispersal area and geometry  
166 and grain size, allow us to discuss the general applicability and reliability of the different methods and to compare the  
167 associated uncertainties.

168

169 **4. Methods and Results**

170 We first present the rationale and the methods used for estimating each different parameter and the related  
171 uncertainty, followed by the results for each deposit. We stress that each unit required different methods to estimate its  
172 parameters.



173 *4.1 Maximum runout and invaded area*

174 In this paper, maximum runout refers to the distance attained by a laterally moving current, and does not include,  
175 for example, distal co-ignimbrite ashfall layers. The problem of tracing the maximum runout of a PDC has not been  
176 previously addressed in detail (Burt et al. 2001). Recently, Gurioli et al. (2010) estimated the maximum runout of PDCs  
177 associated with Plinian and sub-Plinian eruptions at Somma-Vesuvius through the definition of two parameters: the farthest  
178 outcrop distance (the farthest point at which the PDC deposit can still be unambiguously identified); and the maximum  
179 runout (the theoretical distance covered by the PDC before it stopped). Ideally the two distances would coincide in the case  
180 the deposit is completely preserved and fully accessible to investigation. However, the authors underline also that in cases  
181 where the distribution of distal deposits is poorly constrained (particularly for the older eruptions), true maximum runout is  
182 likely is greater in distance than the most distal outcrop. To overcome this ambiguity in the definition of maximum runout,  
183 we suggest to: 1) position a line of maximum runout (MRL) that is based on field data and the sedimentological features of  
184 the deposits; 2) introduce an estimation of the uncertainty on MRL position, following a simplified procedure of expert  
185 judgement to reach consensus between different authors. A similar, simpler approach was adopted by Neri et al. (2015) by  
186 placing a buffer on the deposit boundary with constant range estimated by expert judgment.

187 We structured the procedure for the definition of the MRL (and of the related maximum invaded area - MIA) upon  
188 a sequence of spatial constraints. In particular, in order of decreasing relevance: i) the position of the minimum observed  
189 thickness of the deposit (as directly measured in the field); ii) the presence of topographic obstacles that could have limited  
190 PDC propagation area; iii) the general areal extent of still preserved deposits as derived from available geological maps; iv)  
191 the position of the stratigraphic sections still preserving deposits of the target eruption but which lack the deposits of the  
192 PDC of interest. Given the intrinsic uncertainty in defining the exact position of MRL, we adopt a procedure by which three  
193 different positions for the MRL are traced: a median (or “best guess”) value of this parameter for the specific unit  
194 investigated (the 50<sup>th</sup> percentile outline – MRL<sub>50</sub>) and two uncertainty bounds (the 5<sup>th</sup> and the 95<sup>th</sup> percentiles, that are  
195 MRL<sub>5</sub> and MRL<sub>95</sub>) that take into account the epistemic uncertainty associated with the incomplete knowledge of the deposit.  
196 In other words, while the MRL<sub>50</sub> is defined through the critical analysis of the four different geologic constraints listed  
197 above, the MRL<sub>5</sub> and MRL<sub>95</sub> percentile curves define an uncertainty belt for the maximum runout estimation and represent  
198 the lines having respectively 5% and 95% of probability not to have been overstepped by that PDC. MRL<sub>50</sub> was traced at an  
199 average downcurrent distance no further than 500 m from those stratigraphic sections with the smallest measured thickness.  
200 When tracing the MRL<sub>50</sub>, different segments of the line are distinguished and associated with sectors for which the available  
201 geological constraints on PDC runout have different degrees of confidence (Fig. 4).

202 Once defined, the segments (and sectors), for each of the upper and lower uncertainty bounds (respectively  
203 corresponding to the position of the MRL<sub>5</sub> and MRL<sub>95</sub>) are evaluated. This is a significant novelty compared to the  
204 procedure applied by Neri et al. (2015), where the MRL and its uncertainties were defined without any preliminary  
205 distinction in segments. In this study, four different uncertainty bounds (in terms of distance from the MRL<sub>50</sub>) were applied  
206 and linked to the maximum runout distance reached within the MRL<sub>50</sub> for each unit. Low, moderate, moderate-high and  
207 high uncertainty were estimated in terms of a percentage of the distance with respect to the vent of the maximum runout  
208 distance of the MRL<sub>50</sub>, and corresponding to, respectively, 10%, 5%, 2.5% and 1% of this distance. The distance between  
209 the MRL<sub>5</sub> and MRL<sub>95</sub> is small in cases of sectors with strong geological constraints, while it is larger for those areas where  
210 few outcrops were observed. Conversely, the distance between the MRL<sub>50</sub> and MRL<sub>95</sub> lines has a maximum also for those

211 areas where the thickness of the deposit is more than 1 m (i.e., they do not represent the maximum runout of the PDC). For  
212 all these reasons, upper and lower uncertainty values for a single segment of the  $MRL_{50}$  might be the same (e.g. lower  
213 bound might be -200 m while the upper might be +1000 m with respect to the position of the  $MRL_{50}$ ) depending on the  
214 number of constraints available.

215 The choice of the uncertainty bounds for each segment is based on a simplified “expert judgment” procedure  
216 among the authors of the paper. Although our approach is not structured, as in similar studies (e.g., Selva et al. 2012;  
217 Bevilacqua et al. 2015; Tadini et al. 2017a) it involved a detailed discussion about all the sources of uncertainty for each  
218 segment, detailed in the following, until a consensus was reached about the attribution of the uncertainty bounds. On the  
219 contrary, the uncertainty range was enlarged in cases of discordant views. Based on the comparison with the studies  
220 referenced above, we do not expect that involving other experts will have a large modification on the results, unless new  
221 data or assumptions are introduced into the discussion.

222 In summary, the  $MRL_5$  always represents the line closest to the farthest (and thinnest) deposit measured in the  
223 field.  $MRL_{95}$  approximates the maximum expected runout of a given PDC, based on the critical consideration of all the  
224 geologic constraints that can be used in the expert judgement. In this study we provide three percentile constraints  
225 representing an unspecified probability distribution; this approach is a common practice in expert judgement techniques  
226 (although with differences in distribution types; Cooke 1991; Flandoli et al. 2011), but has been rarely adopted in spatial  
227 mapping problems (see for instance Bevilacqua et al. 2015; Neri et al. 2015; Bevilacqua 2016). Diagrams that illustrate the  
228 preferred directionality in the dispersal of the deposits are given in Fig. 6, where the variation of the distance from the vent  
229 of the MRL for the different studied deposits (and for each of the three isolines traced) is given as a function of the  
230 azimuthal angle with respect to the north. The definition of MRL (and related uncertainty) easily allows us to calculate the  
231 maximum invaded area (and related uncertainty – Table 1) as the area included within each single MRL.

232

#### 233 4.1.1 AD 79 EU3pf

234 The maximum runout distance ( $MRL_{50}$ ) for EU3pf is around 9 km, and therefore the low, moderate, moderate-high  
235 and high uncertainty values are, respectively, 90, 275, 450 and 900 m. The  $MRL_{50}$  is composed of three segments, each with  
236 different uncertainty (Fig. 5a) and identified in Figure 5a with different numbers. Part 1 of  $MRL_{50}$  corresponds to the  
237 segment toward the N, NE and SE with respect to the vent location. This segment is well constrained by numerous  
238 stratigraphic sections where EU3pf is only few centimeters thick, so that the uncertainty on MRL position is low ( $MRL_5 -$   
239  $90m$ ;  $MRL_{95} +90m$ ). Part 2 of  $MRL_{50}$  represents the inland part toward NW. In this case, the constraints are represented by  
240 only a few stratigraphic sections located to the NNW, where the thickness of EU3pf is of the order of few meters, and the  
241 related uncertainty on the position of the MRL has been considered moderate to high ( $MRL_5 -275m$ ;  $MRL_{95} +450m$ ). Part 3  
242 of  $MRL_{50}$  constitutes the seaward part. No constraints are available here except for a few stratigraphic sections near the  
243 coastline where thicknesses are of the order of several meters, making the related uncertainty notably high ( $MRL_5 -450m$ ;  
244  $MRL_{95} +900m$ ). The  $MRL_{50}$  (Fig. 6) varies for the different sectors, passing from about 4 km for the eastern sector, to about  
245 9 km for the south-eastern sector.

246

247

248

249           4.1.2   AD 79 EU4b

250           For the EU4b unit, the maximum runout distance of the MRL<sub>50</sub> is 20 km, and therefore the low, moderate,  
251 moderate-high and high uncertainty values are, respectively, 200, 500, 1000 and 2000 m. The definition of the maximum  
252 runout for the EU4b unit is based on stratigraphic information and on paleo-topographical constraints. EU4c was not  
253 considered in terms of maximum runout as only a very small part of it can be related to deposition from a laterally moving,  
254 highly dilute current, whereas most of this unit was related to fallout deposition from a convective, co-ignimbritic plume.  
255 We have however performed a rough estimation of the area affected by deposition of unit EU4c (using information from  
256 Gurioli 1999) to be used in the following as the integration limit for the calculation of the total grain size distribution of the  
257 eruptive mixture (see section 4.3.2). In order to define the extent of the MRL<sub>5</sub> and MRL<sub>95</sub>, the MRL<sub>50</sub> of EU4b unit was  
258 divided into 4 different segments (Fig. 5b). Part 1 of MRL<sub>50</sub>, representing the inland part toward S and SE, is associated  
259 with a narrow zone of uncertainty (MRL<sub>5</sub> –200m; MRL<sub>95</sub> +200m), resulting from the presence of quite robust constraints  
260 onto the 10 cm isopach (Gurioli et al. 2010) and by the proximity of the MRL<sub>50</sub> to the steep northern slopes of the Sorrento  
261 peninsula (to the SE) and of the Apennines (to the E). Part 2 of MRL<sub>50</sub> corresponds to the seaward part. For this segment  
262 (which is has the highest uncertainty) there is evidence that the PDCs travelled at least 5-7 km across the sea, and reached  
263 the paleo-coastline of the Sorrento peninsula at the S. Maria di Pozzano site (section 203; see Figs. 3 and Online Resource  
264 1). For this reason, the MRL<sub>50</sub> in this sector has been placed at an average distance of 5 km off the coastline and associated  
265 with high uncertainty (MRL<sub>5</sub> –500m; MRL<sub>95</sub> +2000m). Part 3 of MRL<sub>50</sub> represents the inland part toward NW. No strong  
266 stratigraphic (nor topographic) constraints are present here; for these reasons, the uncertainty is moderate-high (MRL<sub>5</sub> –  
267 500m; MRL<sub>95</sub> +1000m). Part 4 of MRL<sub>50</sub> is constituted by the inland part toward N. A stronger constraint here is the  
268 position of the 10 cm isopach (Gurioli et al. 2010). As a consequence, uncertainty in maximum runout can be considered  
269 moderate in this sector (MRL<sub>5</sub> –200m; MRL<sub>95</sub> +1000m). Maximum runout distance occurs in the ESE sector, where the  
270 PDC reached around 20 km from the vent, while in the northern sector, where the initial path of the PDC was possibly  
271 shielded by the high Mt. Somma scarp, the current travelled not farther than 7-8 km (Fig. 6).

272

273           4.1.3   AD 472 F<sub>g</sub>

274           The F<sub>g</sub> unit of the AD 472 Pollena eruption is dispersed in multiple lobes in different sectors of the volcano. In this  
275 study, two different lobes (i.e. the Cupa Fontana and Cupa Olivella; Fig. 5c) have been traced separately and used for the  
276 definition of the maximum runout. Due to the scarcity of measurable outcrops, several cross-sections were traced through  
277 points of measured thickness. Along the cross-sections, the thickness was extrapolated taking into account paleo-  
278 morphology of the substrate (as resulting from field observations) and assuming a horizontal upper surface of the deposit.  
279 Additional information was also derived from the geologic map of Sbrana et al. (2020). This resulted in a significantly  
280 larger set of measured and extrapolated data, used to constrain both isopachs and maximum runout isolines for the two lobes  
281 (Fig. 5c; the complete list of “Measured” versus “Interpolated” thicknesses is provided in Online Resource 4).

282           In contrast to the outlines traced with mainly unpublished data for the two AD 79 PDC units, the MRL<sub>50</sub> was  
283 drawn by simply considering the outline of the preserved deposit of the AD 472 Pollena PDC units in this area. This  
284 approach was preferred over the previous one due the nature of the deposits that clearly derived from a highly concentrated,  
285 rapidly depletive current. Such currents generally pass to en-masse deposition at their distal ends, and terminate with steep-  
286 sided lobes up to decimeters thick (Branney and Kokelaar 2002). Thus, the farthest measured outcrop in this case is at the

287 same time a good approximation of both the best guess and the minimum value to be considered for runout. Consequently,  
288 the MRL<sub>5</sub> and the MRL<sub>50</sub> are considered in this case as coincident. The MRL<sub>95</sub> has been placed at a constant distance of  
289 +200 m with respect to the MRL<sub>50</sub>, as the thicknesses of both the F<sub>g</sub> Cupa Fontana and Cupa Olivella PDC lobes in the  
290 stratigraphic sections close to the MRL<sub>50</sub> are of the order of only few centimeters. This distance corresponds to an  
291 uncertainty between moderate (2.5% of maximum runout distance within MRL<sub>50</sub>) and moderate-high (10% of maximum  
292 runout distance within MRL<sub>50</sub>), since the average MRL<sub>50</sub> is in the range of 5 km from the vent (Fig. 6), both for the Cupa  
293 Fontana and the Cupa Olivella lobes.

294

#### 295 4.2 Volume estimation

296 In contrast to large-volume PDC deposits (see for example Scarpati et al. 2014), estimating the volume of small- to  
297 intermediate-volume PDC deposits is a more difficult task, mainly because deposition from parent PDCs is more strongly  
298 controlled by preexisting topography and cannot be described through a general decay law of thickness that can be  
299 integrated over area (or distance). In addition, the volume of the PDC deposits does not coincide with the volume of the  
300 solid phase transported in the moving PDC, due to redistribution of fine material between the horizontally moving current  
301 and the associated co-ignimbrite plumes. However, the volume of the deposits provides the best proxy for calculating the  
302 solid mass transported by the PDC, as long as uncertainty is explicitly assessed (Sulpizio et al. 2005; Gurioli et al. 2010).  
303 Apart from a few examples (Isaia et al. 2004), there is still no general consensus about the best procedure for volume  
304 estimations of small-scale PDC deposits. To address this problem, in this work six different approaches (summarized in  
305 Table 2) have been used and the results compared to each other. Such approaches have been previously applied mainly to  
306 tephra fallout deposits (Pyle 1989; Fierstein and Nathenson 1992; Bonadonna and Houghton 2005; Bisson and Del Carlo  
307 2013) and to debris avalanche deposits (Crandell 1989).

308 Table 3 reports the percentages of area (with respect to the total dispersal area) enclosed in the MRL<sub>50</sub> which  
309 pertains to each of the three slope classes for all the PDC deposits here considered. Epistemic uncertainty on volume  
310 estimation is mainly based on the lack of direct knowledge about the real extent of the PDC dispersal. This uncertainty has  
311 been included in the following only for the case of the TIN method using the three different maximum runout lines (MRLs)  
312 defined for each unit, considering the area enclosed by the MRL<sub>50</sub> as representative of the expected measure of deposit  
313 dispersal.

314

##### 315 4.2.1 AD 79 EU3pf

316 The dataset used for volume calculations of EU3pf unit consisted of 106 stratigraphic sections (Online Resource  
317 1), while information on 0 m thickness is extracted from the different MRLs. The areal coverage of stratigraphic sections is  
318 moderately dense in the northern sector, due to the presence of numerous valleys and road cuts. Using the thickness values,  
319 segments of three different isopachs were also drawn (Fig. 5a) and used for volume calculations.

320 Four different methods (CRh, CRs, VOR and TIN; Table 2) were used for estimating the volume of this unit; three  
321 of these (CRh, CRs, VOR) were used to calculate volume within the MRL<sub>50</sub> only, while for TIN method the volume was  
322 calculated considering the deposit enclosed by the MRL<sub>5</sub>, MRL<sub>50</sub> and MRL<sub>95</sub>, in order to estimate the uncertainty on the  
323 measure.

324 The sectors for the application of methods CRh and CRs were defined as follows: (1) for the CRh method, EU3pf  
325 deposit was divided into four areas, corresponding to different fans in the NW, NE, SE and SW sectors of the volcano (and  
326 mainly related to the paleotopography; Fig. 5a); (2) for the CRs method, EU3pf deposit was divided into three sectors using  
327 the three different slope classes defined in Table 3. The VOR method was applied to the total dataset of available thickness  
328 data. The uneven distribution of the points, and especially the lack of points in the proximal (less than 4 km distance from  
329 the vent) and in the eastern sectors, imply the tracing of very large Voronoi cells, resulting in a low reliability to the volume  
330 estimate. In the application of the TIN method, the EU3pf deposit was further subdivided into a northern and a southern  
331 zone (Fig. 5a) in order to account for the blocking effect of the Mt. Somma scarp, and separated volumes were calculated  
332 accordingly.

333 All volume estimations are shown in Table 4. With respect to the TIN estimations, it is evident how the two sectors  
334 (N and S) have substantially the same volume of deposit. Results show that the sectorialization CRs methods tend to  
335 produce volume estimates up to 40% higher with respect to the TIN method. Even larger estimates (50% larger with respect  
336 to the TIN method) derive from the use of VOR method. Uncertainty on volume estimation based on the TIN method (as  
337 calculated respect to the uncertainty on the invaded area) is slightly asymmetric with respect to the median value (-19% and  
338 +28%), and well below the differences with respect to the volume values obtained with the other methods.

339

#### 340 4.2.2 AD 79 EU4

341 For the EU4 unit, volume was assessed in a detailed way only for EU4b (Table 5), as this is the only bed that can  
342 be directly related to deposition from a PDC. For this estimate, a total of 102 stratigraphic sections were used (Fig. 5b).  
343 Thickness data were used to trace 7 isopachs, from 0.1 m to 4 m (Fig. 5b). Volume of the EU4b unit was estimated  
344 following methods CRs, TR, PY, VOR and TIN (Table 2). An estimation on the volume for unit EU4c was also performed,  
345 in order to refine the calculation of the TGSD of the collapsing mixture (see section 4.3.2), and to estimate the relative  
346 amount of material. This estimation (0.034 km<sup>3</sup>) was performed using the TIN method and the outline of Fig. 7c as  
347 integration limit.

348 As for the EU3pf, methods CRs and VOR give the highest volume estimates, respectively, of 90% and 70% higher  
349 with respect to the volume calculated using the TIN method. Volumes estimated with method TR and method PY (with two  
350 segments approximation) are only slightly higher (+24% and +15% respectively) than that from the TIN method. Due to the  
351 integration up to an infinite area of method PY, the result of this calculation could represent a maximum value for the  
352 volume of the deposit. Finally, the TIN method was applied to calculate the volume using points on the three MRLs as zero-  
353 thickness points, in order to have an estimation of the uncertainty related to the maximum dispersal area, which is however  
354 moderately low (Table 5). The small uncertainty in the calculation of volume derives from the continuous and nearly regular  
355 thinning with distance of the EU4b deposit, with low values of thickness measured at the most distal sites.

356 Because of the asymmetric dispersal of the EU4b deposits (the maximum runout distance for the southern  
357 quadrants is larger on average with respect to that for the northern quadrants; Figs. 5b and 6) the deposits have been  
358 subdivided into two distinct areas: NW and SE. These partitions were defined by drawing a straight line (dashed green line  
359 in Figs. 5b and 7b) perpendicular to the axis of maximum elongation of the deposit (oriented roughly NW-SE). Despite the  
360 larger area of the SE sector with respect to the NW, the volume results are more or less evenly distributed between the two

361 sectors (60% vs. 40%, respectively; Table 5), due to the generally lower thickness of the deposits of the SE sector, which is  
362 probably related to the gentler slope and lower topographic roughness.

363

#### 364 4.2.3 AD 472 $F_g$

365 Volume estimations for the two  $F_g$  PDC lobes from the AD 472 Pollena eruption utilized a total of 27 stratigraphic  
366 sections (6 measured and 21 interpolated), and 31 sections (12 measured and 19 interpolated) for the Cupa Fontana and  
367 Cupa Olivella, respectively. Thicknesses range between 1 cm and 4.8 m. Volumes were calculated with methods CRs, VOR  
368 and TIN (Table 2), all referred to the  $MRL_{5/50}$  (Table 6).

369 The deposits volumes for these very restricted lobes are small: an order of magnitude lower than those calculated  
370 for EU4b. This possibly reflects the lower intensity of this eruption with respect to the AD 79 eruption. Relative uncertainty  
371 in the estimate is related to the extent of the invaded area which was evaluated by comparing the volumes within the  
372  $MRL_{5/50}$  and the  $MRL_{95}$  with the TIN method. This uncertainty is however of similar magnitude to the two larger PDC  
373 deposits, and varies from 10% to 17% of the estimated volume (for the Cupa Fontana and Cupa Olivella lobes,  
374 respectively). As for the other two cases discussed above, the lower volume values are returned by the TIN method, while  
375 the use of the CRs method results in values nearly double those derived from the TIN method. The volume calculated with  
376 the VOR method gives higher, but largely variable, values with respect to the TIN method (30% and 80% respectively, for  
377 the two lobes). This is possibly related to the low number of sites available for measuring thickness in the field, which are  
378 generally restricted to the upstream part of the two lobes and have high thickness values.

379

#### 380 4.3 Total Grain Size Distribution (TGSD)

381 The Total Grain Size Distribution (TGSD) of PDC deposits represents an important parameter for the  
382 understanding of physical processes involved in transport and deposition from these currents and for numerical modeling  
383 related to hazard assessment. In this study, we applied and compared two methods for TGSD calculation (Table 7): (1) the  
384 Voronoi tessellation method (Bonadonna and Houghton 2005), using as the integration limit the  $MRL_{50}$  for units EU3pf,  
385 EU4b and  $F_g$  (Fig. 7); (2) the Walker (1980) method (referred to from now on as “isomass method”) integrating the  
386 resulting plot of mass per area for each grain size class  $\Phi$  ( $M/A_\Phi$ ) vs. the square root of the area ( $A^{1/2}$ ) of each isomass  
387 curve through the formula of Fierstein and Nathenson (1992). Grain size analyses were performed in the interval  $-4\Phi$  to  $5\Phi$   
388 at  $1\Phi$  interval. For stratigraphic sections with more than one sample, the average grain size of the section was calculated by  
389 averaging all the grain size analyses of samples collected at that section. Density values for the PDC deposits were directly  
390 measured on several samples. In the supporting information we are providing the following detailed data: (1) grain size  
391 analyses for all units (Online Resource 2); (2) deposit density measurements (Online Resources 3 and 4); (3) distribution of  
392 stratigraphic sections for all units (Online Resource 5); (4) TGSD numerical values and subpopulations data (Online  
393 Resource 6) and; (5) isomass maps for units EU4b and EU4c (Online Resources 7, 8, 9, 10). TGSD data are generally  
394 polymodal, and in many cases the classical grain size distribution parameters are not appropriate to fully describe the whole  
395 distribution. For this reason, TGSD data have been deconvoluted into multiple Gaussian subpopulations (SP) using the SFT  
396 software (Wohletz et al. 1989), and for each subpopulation the median value, the standard deviation and percent by weight  
397 with respect to the total sample have been calculated. Due to the lower limit of the sieving ( $5\Phi$ ), one SP was arbitrarily

398 placed around this diameter, and the median value of this should be considered as “finer than  $5\Phi$ ”. In the studied examples,  
399 this fine-grained SP represents from 1 to 15 % of the total.

400 The calculated TGSDs for the PDC deposits, whatever the method used, are only representative of the lapilli to  
401 coarse ash fractions of the original pyroclastic mixture carried by the PDC. Estimation of the finer-grained fractions is  
402 complication by elutriated by ash production by clast comminution and abrasion during the transport. Here, we attempted to  
403 estimate the contribution to the TGSD of the elutriated ash deposited from the co-ignimbrite cloud for the EU4 unit using  
404 data for EU4c sub-unit. Table 7 summarizes the information related to TGSD estimation for all the studied units.

405

#### 406 4.3.1 AD 79 EU3pf

407 TGSD was calculated for this unit only using the Voronoi method, as no simple fit was possible on an  $\ln M/A_\phi$  vs.  
408  $A^{1/2}$  plot for using the “isomass method”. As in the case of the volume calculation, TGSD was calculated both for the total  
409 deposit (Fig. 7a), and for the N and S sectors (separated by the green dashed line of Fig. 5b) for the same reasons. TGSD for  
410 the different sectors are however nearly coincident (Fig. 8a), the main difference being related to a larger (around 5%)  
411 amount of fine ash ( $\Phi > 5$ ) in the deposits dispersed to the south. Resulting total TGSD is nearly unimodally distributed,  
412 with a main mode at  $0.5\Phi$  representing around 92 % of the total (Online Resource 6). F1 value (wt. % of ash finer than  $0\Phi$ ;  
413 Walker 1983) is around 40 %, while F2 (wt. % of ash finer than  $4\Phi$ ; Walker, 1983) is slightly more than 10 %.

414

#### 415 4.3.2 AD 79 EU4

416 EU4 represents an unusual case in which both the deposits of a PDC (EU4b unit) and those of the associated co-  
417 ignimbrite cloud (EU4c unit) can be recognized and mapped in the field. For this reason, it was possible to estimate the  
418 TGSD for the two units, the weighted sum of which (EU4b/c) can be considered a good approximation of the TGSD of the  
419 pyroclastic material in the collapsing column. The distribution of the sections and the related Voronoi polygons used for the  
420 TGSD estimations for EU4b and EU4c are shown in Fig. 7b and 7c respectively.

421 TGSD with the Voronoi method for the EU4b unit is shown in Fig. 8b, both for the whole deposit and for the NW  
422 and SE sectors. The results from the two sectors are very different, with TGSD for the SE sector being more fines-rich  
423 compared to the NW sector: the value of F1 in the SE is nearly double respect to that in the NW). When integrated with  
424 respect to the mass distributed over the two sectors, the TGSD results are strongly platykurtic and polymodal.

425 The comparison of TGSD of EU4b (Fig. 9) calculated with the different methods suggests that: (1) the Voronoi  
426 tessellation method tends to estimate a lower amount of fine materials with respect to the isomass methods; (2) the  
427 estimations, performed by integrating different approaches to the isomass maps, show an irregular distribution with a  
428 marked polymodality (4 main subpopulations; Online Resource 6).

429 The dispersal outline used for tracing the isomass maps is the same used in section 4.2.2 for volume calculations.  
430 TGSD is strongly asymmetric, with a main mode between  $2.5$  and  $3.8\Phi$  (Online Resource 6) and more than 90 wt% of ash  
431 finer than  $0\Phi$ . The total mass of EU4c, which represents around 10% of the mass of EU4b, was calculated by multiplying  
432 the mean density of the deposit (Table 7) by the estimated volume of EU4c (see section 4.2.2). Summing up the TGSD data  
433 of EU4b and EU4c units, after weighing for their total mass, we obtained a TGSD (EU4b/c) that can be considered  
434 representative of the distribution of the erupting mixture ejected from the vent. This latter is characterized by a very poorly  
435 sorted, polymodal distribution, with at least 4 subpopulations (Fig. 9c; Online Resource 6). With respect to the TGSD of

436 Fig. 9, it should be specified that at the current stage the position of the mode at the  $\Phi=5$  size should be considered an  
437 artifact, as data for the  $\Phi=5$  class represent a total of all the grain sizes finer than that class.

438

#### 439 4.3.3 AD 472 $F_g$

440 Given the limited dispersal and the very similar facies characteristics of the deposits throughout their dispersal, the  
441 TGSD for the Cupa Fontana and the Cupa Olivella lobes was tentatively estimated only through the Voronoi method (Fig.  
442 7d).

443 TGSD for both of the lobes are shown in Fig. 8c. It is evident the similar modal value for the two lobes (between 0  
444 and -0.6  $\Phi$ ; Table 5SM), and the more fines-rich nature ( $F1=32\%$ ) of the Cupa Olivella with respect to the Cupa Fontana  
445 lobe ( $F1=23\%$ ), are possibly related to the availability of samples from more distal sites in the former (Fig. 7d).

446

## 447 5. Discussion

448 Estimating the natural variability and related uncertainties of physical parameters like maximum runout distance,  
449 volume, and total grain size distribution of PDC deposits is complicated due to the intrinsic variability of dispersal and  
450 sedimentological characteristics. Any study with these goals must begin with a detailed field analysis of the lithofacies  
451 associations in the deposits (Branney and Kokelaar 2002; Sulpizio and Dellino 2008), in order to select the most appropriate  
452 methods for the calculation of these parameters. Many field measurements (thickness of different units, density of the  
453 deposit) and samples should be collected, especially from areas where the PDC was emplaced over rugged  
454 paleotopography. The three cases discussed above for Somma-Vesuvius represent a range of PDC types, allowing us to  
455 infer the main factors controlling their main parameters (volume, invaded area, runout distance and TGSD), to statistically  
456 compare the methods for their estimation, and to quantify, for the first time, a comprehensive range of these parameters for  
457 different PDC deposits that will be useful for future application of numerical models and hazard assessments at the volcano.  
458 We think that the goal of a robust reconstruction of the properties of past PDC is not in contradiction with the presence of  
459 uncertainty and it should deal with it specifically.

460

### 461 5.1 MRL and MIA estimations

462 Estimation of maximum runout and invaded area (MRL and MIA, respectively) define the possible area impacted  
463 by a PDC. Several considerations can be made with respect to the methods for the definition of the maximum runout  
464 outlines of past events based on incomplete stratigraphic records. While the occurrence at distal sites of thin PDC deposits  
465 can be used for assessing minimum runout distances, it is difficult to constrain the distance at which the related PDC  
466 actually stopped and/or lifted off based solely on deposit evidence (Andrews and Manga 2011). Thus, the rationale used for  
467 constraining MRL and MIA varies on a case by case base.

468 The topography surrounding Somma-Vesuvius exerts a first-order control on maximum runout. This is especially  
469 true in the case of PDCs with a runout of at least 10 km where low values of the thickness of the deposit coincide with the  
470 onset of a positive gradient in the local topography. Areas with the highest degree of uncertainty in maximum runout are  
471 those located in sectors where stratigraphic information is confined to proximal sites or where the PDCs entered the sea.  
472 Documented cases elsewhere show that PDCs can either travel long distances over the water, or stop rapidly (Carey et al.  
473 1996; Cole et al. 1998). The presence of EU4b deposits on the northern side of the Sorrentina peninsula (Figs. 1 and 3;



474 Cioni et al. 1992) is direct evidence of the ability of the PDC to travel over the sea for at least 7-8 km, passing across the  
475 Gulf of Napoli (Fig. 1). Evidence for dense, granular PDCs entering the sea is reported for the AD 1631 sub-Plinian  
476 eruption (Rosi et al. 1993): numerous paintings (e.g. Giovan Battista Passeri, “Vero disegno dell’incendio del mons Vesuvii  
477 1631”) illustrate PDCs stopping only a few hundred meters after entering the sea. Definition of the maximum invaded area  
478 and hence of the maximum runout lines for this side of the volcano for our study cases is consequently largely inferred.  
479 Since in all these cases there is a large uncertainty in the position of MRL, the need for a quantitative range justifies the  
480 application of expert judgement techniques to deal with it (Neri et al. 2014, 2015).

481 Additional information for the definition of the maximum runouts and of their uncertainties could be derived from  
482 observations on PDC deposits. For those related to concentrated PDCs (AD 472 F<sub>g</sub>), topography was the main controlling  
483 factor on their dispersal, and topographic features could be used to constrain maximum runouts. For deposits of dilute PDCs  
484 (AD 79 EU3pf and EU4b), the steep decrease of thickness with distance implies that the presence of thin (less than 10 cm  
485 thick) massive, ash-dominated deposits at distal sites can be interpreted as good evidence of proximity to the maximum  
486 runout distance, with a consequent lower uncertainty in its definition.

487 In the absence of direct data, and associated uncertainty, the use of different limits representing the reconstructed  
488 maximum runout distance assessed in probabilistic terms (MRL<sub>5</sub>, MRL<sub>50</sub>, and MRL<sub>95</sub>) appears an effective way to quantify  
489 the uncertainty on the estimate of this parameter. The position of the upper and lower uncertainty bounds are more  
490 amenable to expert judgement.

491 As a consequence of large uncertainty in estimating maximum runout, estimates of the invaded area (MIA) are also  
492 uncertain. The selected examples entail a wide variation, with MIAs varying from less than 10 km<sup>2</sup> (in case of AD 472 F<sub>g</sub>  
493 lobes) up to more than 500 km<sup>2</sup> (in the case of AD 79 EU4b). Uncertainty is generally not symmetric with respect to the  
494 reference value (MIA corresponding to the MRL<sub>50</sub>), and is generally lower for the lower bound (varying from 0 to 14%  
495 relative) and larger for the upper bound (from 14 to 30%). Total uncertainty on area is however estimated around 15-20%  
496 for the two small lobes of F<sub>g</sub>, while it varies between around 25 and 40% for the widespread deposits related to turbulence-  
497 dominated PDC (EU3pf, EU4b). We suggest that these percentages should be considered as first-order reference values for  
498 uncertainty when assessing the area invaded by a PDC, especially in studies related to emergency planning.

499

## 500 *5.2 Volume estimation*

501 The evaluation of the volume of a PDC deposit is the first, necessary step to define the mass of magma (and  
502 possibly non-juvenile material) dispersed by a PDC and is a fundamental parameter needed to physically describe and  
503 realistically model the current. The volumes of the different PDC deposits examined here have been estimated using  
504 different approaches, and their comparison can provide preliminary estimates of the method-related uncertainty. Due to the  
505 non-regular spatial thickness variability of PDC deposits, the different approaches give in general quite different results, due  
506 to the implicit differences in the area integration of thickness data. The TIN method represents a simpler way of  
507 extrapolating thickness on the basis of a randomly spaced dataset of measured points. This is an advantage in the absence of  
508 theoretical models able to derive a physical law for thickness variation with distance. In particular, the TIN method can be  
509 also enhanced if, in addition to the measured data, inferred/hypothetical data can be added to the available dataset, based on  
510 the observation of the paleotopography and some basic assumptions on the geometry of PDC deposits (see data used for F<sub>g</sub>  
511 unit). However, the comparison of TIN with other methods is a key to the estimation of the related uncertainty. In particular,

512 we observe that: a) the CRh and CRs methods generally result in the largest volume estimations, since the mean thickness  
513 values attributed to each sector are generally skewed toward higher values (thick deposits are better preserved than thin  
514 ones); b) the VOR method tends to reduce the thickness variation of the deposit (since it creates polygons with a constant  
515 thickness), resulting in a poorly controlled variability of the total volume, especially in the presence of a low number of  
516 measured sites and rugged basal topography; c) due to the difficulty of tracing isopach maps for PDC deposits (dispersal is  
517 generally heavily irregular), also data derived from the TR method tend to be biased toward high values, however its results  
518 are more similar to those of the TIN method. Similarly to the trapezoidal rule, the PY method can give results that well  
519 agree with those derived from TIN, but in this case it is fundamental to trace an isopach with an arbitrarily low value of  
520 thickness (however different from 0, we suggest here, by reference, a 1 mm thickness) in coincidence with the position of  
521 MRL. A very large envelope of the method-related uncertainty is derived for the PDC volume (from 50 to 100% respect to  
522 the output of the TIN method). In addition, considering only the TIN method, we estimated the effects over the volume  
523 value of the epistemic uncertainty in the extent of dispersal area (i.e. the  $MRL_{50}$  and  $MRL_{95}$ , as discussed for the evaluation  
524 of the maximum runout). In this case, the total uncertainty is generally lower, and is placed between 10% and a maximum  
525 of 45%. We note that such uncertainty is lower for deposits that show a sharp decrease in thickness with distance (in our  
526 case EU4b), for which the large uncertainty in the definition of the invaded area does not reverberate with the same weight  
527 on the uncertainty in the volume (as thickness associated to the uncertainty belt around the  $MRL_{50}$  is low). Conversely,  
528 where thickness is poorly correlated with distance, the uncertainty is larger. We can therefore conclude, similarly to the  
529 maximum runout case, that the identification and measurement in the field of thin distal deposits is a fundamental  
530 requirement for robustly constraining volume estimates.

531 The volume of material initially transported by a PDC is different from the volume of its deposit. This is because a  
532 portion of the finer-grained pyroclasts are transferred into the convective, co-ignimbrite plume and are ultimately deposited  
533 as fallout material. The estimation of this part of the deposit is always problematic, as co-ignimbrite material is both mixed  
534 in the upper portion of the PDC-related deposit or has a largely different dispersal respect to the PDC deposit. The  
535 partitioning of pyroclasts between the PDC and its co-ignimbrite cloud are strongly related to PDC dynamics and initial ash  
536 content (Engwell et al. 2016). The AD 79 EU4 unit represents a good case for trying to estimate the relative amount of co-  
537 ignimbrite material associated with this PDC, as the co-ignimbrite ash deposits of the EU4c unit can be mapped. Results  
538 suggest that the material associated with this unit is at least around 10% (Table 5) of the volume of the PDC deposit: this is  
539 consistent with similar estimates derived from multiphase flow modeling of PDCs (e.g. Neri et al. 2002; Di Muro et al.  
540 2004). The value calculated for the EU4 unit should be considered as an order of magnitude indication of the possible  
541 release of fine material to the atmosphere from a turbulent, diluted PDC of intermediate volume.

542

### 543 *5.3 TGSD estimations*

544 Despite the importance of this eruption source parameter for the application of several numerical models  
545 describing PDC dynamics, TGSD data for PDC deposits are generally not available in the literature due to the large  
546 variability of the grain size features of PDC deposits and to the sometimes erratic and spatial variability of thickness. Even  
547 when obtained, deriving TGSD from the integration over the entire deposit is not guaranteed to obtain a true representation  
548 of the initial TGSD of the pyroclastic mixture for three main reasons: i) coarse, proximal deposits are often under-  
549 represented by exposures or by the blockage effects of topographic obstacles such as caldera rims like at Somma-Vesuvius

550 (Valentine et al. 2019; Valentine 2020); ii) part of the finer-grained material present in the erupting mixture is not deposited  
551 by the PDC, and instead is incorporated into the buoyant part of the PDC and redistributed over by atmospheric advection  
552 and fallout deposition; iii) the grain size distribution of solid material carried in the current is continuously modified by  
553 abrasion and breakage of particles during transport (Manga et al. 2011; Kueppers et al. 2012; Mueller et al. 2016). These  
554 latter two processes are difficult to model accurately or describe quantitatively, and therefore TGSD data extracted from  
555 deposits should be considered as only a first order approximation of the initial TGSD.

556 From the discussion above, it is clear that in the estimate of the TGSD of a PDC there are different sources of  
557 epistemic uncertainty, and we suggest therefore that the usage of different methods for the estimation of the TGSD is the  
558 most efficient way to derive a first order estimate for TGSD (and hence of its uncertainty).

559 The data reported in this paper are therefore mainly addressed to quantify (and whenever possible, to reduce) the  
560 first source of uncertainty and, although they present large limitations, they still reveal significant differences in the initial  
561 TGSD for the deposits of different types of PDCs, that can be useful for modeling purposes.

562 Data on AD 79 EU4 unit allow us to discuss the underestimation of the fine-grained portion implicit in these  
563 TGSD estimations. From the presented results, the co-ignimbritic material represents around 10% of the total mass involved  
564 in the PDC formation, and the contribution of this mass (dominated by fine-grained material) to the TGSD of the whole  
565 PDC is changes it into a strongly platykurtic, poorly sorted distribution without any prominent modal class. To help  
566 constrain numerical modeling of PDC generation more data of this type should be derived for other units with different  
567 sedimentological features, whenever it is possible to trace the dispersal of both the PDC and the associate co-ignimbrite  
568 deposits.

569

#### 570 *5.4 Numerical modeling of PDCs and applicability of the proposed approach*

571 The data here presented, and especially the proposed comparative approach to estimate MRL, invaded area,  
572 volume or TGSD for the different types of PDC from Somma-Vesuvius, is useful for defining the main input parameters for  
573 the physical modeling of such events, and for ascribing uncertainty ranges to such parameters which are critical for  
574 probabilistic, hazard-oriented studies (see for instance Tierz et al. 2018). The large variability of basic assumptions or  
575 general complexity of physical models for PDC (Roche et al. 2013; Dufek et al. 2015) reflects the different input data  
576 needed for their initialization or calibration. In particular, MRLs is an important parameter used to calibrate simplified  
577 kinetic models (energy cone, Malin and Sheridan 1982; Aravena et al. 2020; box-model, Esposti Ongaro et al. 2016), by  
578 applying match procedures to areal extent (Tierz et al. 2016) or maximum runout limits. The proposed methodology for the  
579 estimation of the associated uncertainty is of importance for these very simplified models, as uncertainty propagates into the  
580 final hazard maps largely by contributing to the define extents of the areas with different probabilities of invasion. In  
581 addition, volume, sometimes together with MRL, is a basic parameter to initialize either kinetic or depth-averaged models  
582 (VolcFlow, Kelfoun and Druitt 2005; Gueugneau et al. 2020; TITAN2D, Patra et al. 2005, 2020) and, despite the  
583 uncertainty in its calculation (see section 5.3), even TGSDs might be employed efficiently within numerical models. In  
584 particular, TGSD could be either used whole for some models (Biagioli et al. 2019; Aravena et al. 2020) or to derive  
585 representative grain size parameters such as, the Sauter mean diameter (Breard et al. 2019; Valentine 2020).

586 The approach presented here has been tested on a large, but not completely exhaustive, spectrum of PDC deposits,  
587 so that it can be taken as a first reference for the definition of such parameters at other volcanoes. The approach can be

588 enlarged, without applying substantial modifications, to comprise other types of deposits. As an example, MRL or volume  
589 of very coarse grained PDC deposits, like classical block-and-ash flow deposits not specifically considered here, could be  
590 estimated using an approach similar to that used for the channelized lobes of the AD 472 eruption. Conversely, TGSD  
591 estimates for these type of deposits would need a more accurate consideration of the coarse material, which could be done,  
592 for example, by integrating the results of dedicated image analyses techniques (Sarocchi et al. 2011). More importantly, the  
593 proposed approach also allows a more direct comparison of parameters like volume or TGSD of PDC with those of fallout  
594 deposits, for which well-defined procedures are already realized. This would enable a complete quantitative description of  
595 the deposits of complex, multiphase explosive eruptions (Sulpizio et al. 2005).

596 Our data clearly demonstrate the need for the collection of a detailed dataset of volcanological and  
597 sedimentological characteristics of different types of PDC deposits at a volcano to reach a breakthrough in the quantification  
598 of the main physical parameters which can characterize the PDCs. While it is clear that this is not possible at every volcano,  
599 the results from Somma-Vesuvius could help a first approximation of the level of uncertainty related with the estimation of  
600 these parameters elsewhere.

601

## 602 **6. Conclusions**

603 Parameters related to PDC deposits and relevant to physical modeling and numerical simulation of PDCs have  
604 been estimated and discussed in detail using a large dataset on the deposits of different types of PDCs at Somma-Vesuvius  
605 volcano. These parameters are maximum runout distance (MRL), maximum invaded area (MIA), volume, and total grain  
606 size distribution (TGSD). The lack of protocols for the estimation of these parameters has been here overcome by using  
607 different approaches and comparing and discussing the results obtained by different methods to extract the absolute value  
608 and related uncertainties of these parameters. This multiple approach currently represents the best way to extract a range of  
609 reliable values of all these parameters. The large variability of the inferred physical properties of the different PDCs  
610 considered here, whose deposits were dispersed over similar topography, permit first comparison of the natural variability  
611 of these eruptive parameters. In addition, the moderately large variability in dispersal area, volume, lithology and transport  
612 processes of the studied cases allow us to draw some general conclusions that are useful for the derivation of established  
613 protocols of calculation for the different parameters of small- to intermediate-scale PDC deposits.

614 The main results derived from the study are: (1) the uncertainty in the definition of the maximum runout line can  
615 be expressed by using three different reference isolines ( $MRL_5$ ,  $MRL_{50}$ , and  $MRL_{95}$ ), whose positions were defined by using  
616 non-formalized expert judgement pooling; (2) the extension of Maximum Invaded Area (MIA) and related uncertainty are  
617 directly derived from the different MRLs traced for a given deposit. For the Somma-Vesuvius case, the uncertainty on the  
618 invaded areas is quite high (up to 40% of the area related to the  $MRL_{50}$ ), and this should be kept in mind for hazard  
619 assessment; (3) the volume of PDC deposits is hard to estimate due to the lack of regularity of thickness with distance from  
620 the eruptive vent. By adopting the TIN method and by using the uncertainty on the invaded area to estimate the uncertainty  
621 on volume, it is possible to derive an uncertainty in the range 10-45% of the median volume estimate. Lower uncertainties  
622 are associated with deposits showing a marked decrease of thickness with distance; (4) TGSD has been here estimated using  
623 the two main approaches already in use for fallout deposits (i.e. the Voronoi and isomass methods). Results are largely  
624 variable in terms of relative amount of single grain size classes, and the comparison of the two methods can provide a

625 general trend of the TGSD. In the studied units, co-ignimbrite deposits have been estimated to account for around 10% of  
626 the total mass involved in the PDC formation, an amount that can strongly modify the final TGSD estimation.

627 The numerical estimates and associated uncertainties obtained in this paper for three different types of PDCs at  
628 Somma-Vesuvius, represent the first attempt to constrain some of the most important parameters characterizing PDC  
629 formation and deposition, and should be used in the future as input data for hazard assessment studies at the volcano. We  
630 hope our approach could be strengthened by applying it to other volcanoes once new field data are available. Future work  
631 needs to address several unresolved issues, such as the mobility of PDCs above water (and therefore the maximum runout  
632 for the seaward parts of PDC deposits), the decay trend of thicknesses with distance (with implications for volume  
633 calculations) and the link between the TGSD calculated from deposit data and the initial TGSD erupted from the volcanic  
634 vent (with strong implications for numerical modelling).

635

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637

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815

816

## 817 **FIGURE CAPTIONS**

818 **Figure 1** Landsat image of the Somma-Vesuvius area highlighting the localities cited in the text (courtesy U.S. Geological  
819 Survey, Department of the Interior). Coordinates are expressed in the UTM WGS84 33N cartographic system.

820

821 **Figure 2** a) the EU3pf unit; b) the EU4 unit (with levels a, b and c); c) the F<sub>g</sub> unit.

822

823 **Figure 3** stratigraphic sections used to calculate the parameters of the EU3pf, EU4 and F<sub>g</sub> (Cupa Olivella and Cupa Fontana  
824 lobes) units. Vent positions, vent uncertainty areas and Somma-Vesuvius caldera outline as defined in Tadini et al. (2017b).

825

826 **Figure 4** example of the identification of two segments (Segment 1 in light orange and Segment 2 in dark orange) for the  
827 MRL<sub>50</sub> of the EU4b unit. Starting from these two segments (and from the others that compose the whole outline), different  
828 uncertainty bounds are traced according to the amount and quality of the constraints available (inclined topography,  
829 proximity and thickness of stratigraphic sections, isopach lines).

830

831 **Figure 5** a) MRL outlines and isopachs related to the EU3pf unit. The green dashed line identifies the north and south  
832 sectors used for volume and TGSD calculations; b) MRL outlines and isopachs related to the EU4b unit. The dark green



833 dashed line identifies the NW and SE sectors used for volume and TGSD calculations; c) MRL outlines related to the F<sub>g</sub>  
834 Cupa Fontana and Cupa Olivella lobes. Preserved PDC deposits related to the AD 472 eruption (Santacroce and Sbrana  
835 2003) are also shown. Vent positions, vent uncertainty areas and Somma-Vesuvius caldera outline as defined in Tadini et al.  
836 (2017b).

837

838 **Figure 6** MRL outlines for the EU3pf and EU4b units and for the F<sub>g</sub> Cupa Olivella and Cupa Fontana lobes as a function of  
839 the angle (in degree) from the North (in clockwise direction).

840

841 **Figure 7** stratigraphic sections with samples and related Voronoi polygons used to calculate the TGSD of the: a) EU3pf  
842 unit. The green dashed line identifies the north and south sectors used for TGSD calculations; b) EU4b unit. The dark green  
843 dashed line identifies the NW and SE sectors used for TGSD calculations; c) EU4c unit; d) F<sub>g</sub> (Cupa Olivella and Cupa  
844 Fontana lobes) unit. Vent positions, vent uncertainty areas and Somma-Vesuvius caldera outline as defined in Tadini et al.  
845 (2017b).

846

847 **Figure 8** TGSD calculated by using the Voronoi tessellation method for the a) EU3pf (Total, North and South sectors), b)  
848 EU4b (Total, NW and SE sectors) and c) F<sub>g</sub> (Cupa Olivella and Cupa Fontana lobes) units.

849

850 **Figure 9** a) TGSD calculated for the EU4b unit by using the Voronoi tessellation method, the Isomass method with the  
851 formula of Pyle (1989) and the Isomass method with the Weibull function (Bonadonna and Houghton 2005); b) TGSD  
852 calculated for the EU4c unit by using the Voronoi tessellation method and the Isomass method with the formula of Pyle  
853 (1989); c) TGSD calculated for the EU4b/c unit (levels b and c considered together) by using the Voronoi tessellation  
854 method and the Isomass method with the formula of Pyle (1989).

855

## 856 **TABLE CAPTIONS**

857 **Table 1** Maximum invaded areas (MIAs) for all the PDC units discussed. F<sub>g</sub> CO and F<sub>g</sub> CF are related to, respectively, to  
858 the Cupa Olivella and Cupa Fontana lobes.

859

860 **Table 2** Methods used for volume estimation. Method names are: “CRh” – Crandell version 1; “CRs” – Crandell version 2;  
861 “TR” – trapezoid; “PY” – Pyle; “VOR” – voronoi; “TIN” – triangular irregular network.

862

863 **Table 3** Slope classes, percentages of the MIA related to the MRL<sub>50</sub> which belong to one of the three slope classes, number  
864 of stratigraphic sections which fall into one of the three slope classes and average thicknesses of the above-mentioned  
865 sections for all the units/lobes.

866

867 **Table 4** volume estimations for the EU3pf unit using methods CRh, CRs, VOR and TIN.

868

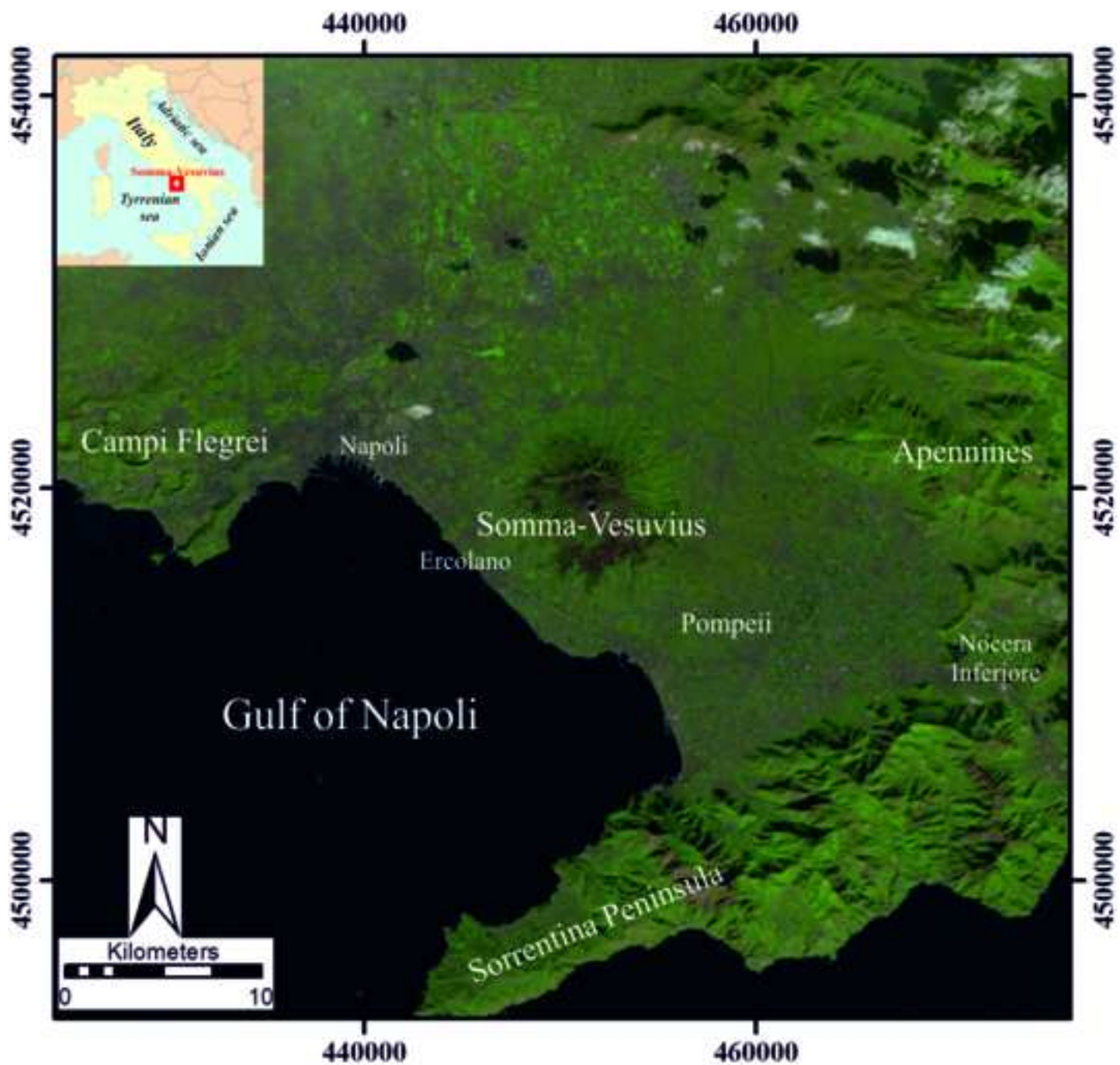
869 **Table 5** Volume estimations for the EU4 unit (level b) using method CRs, TR, PY, VOR and TIN.

870

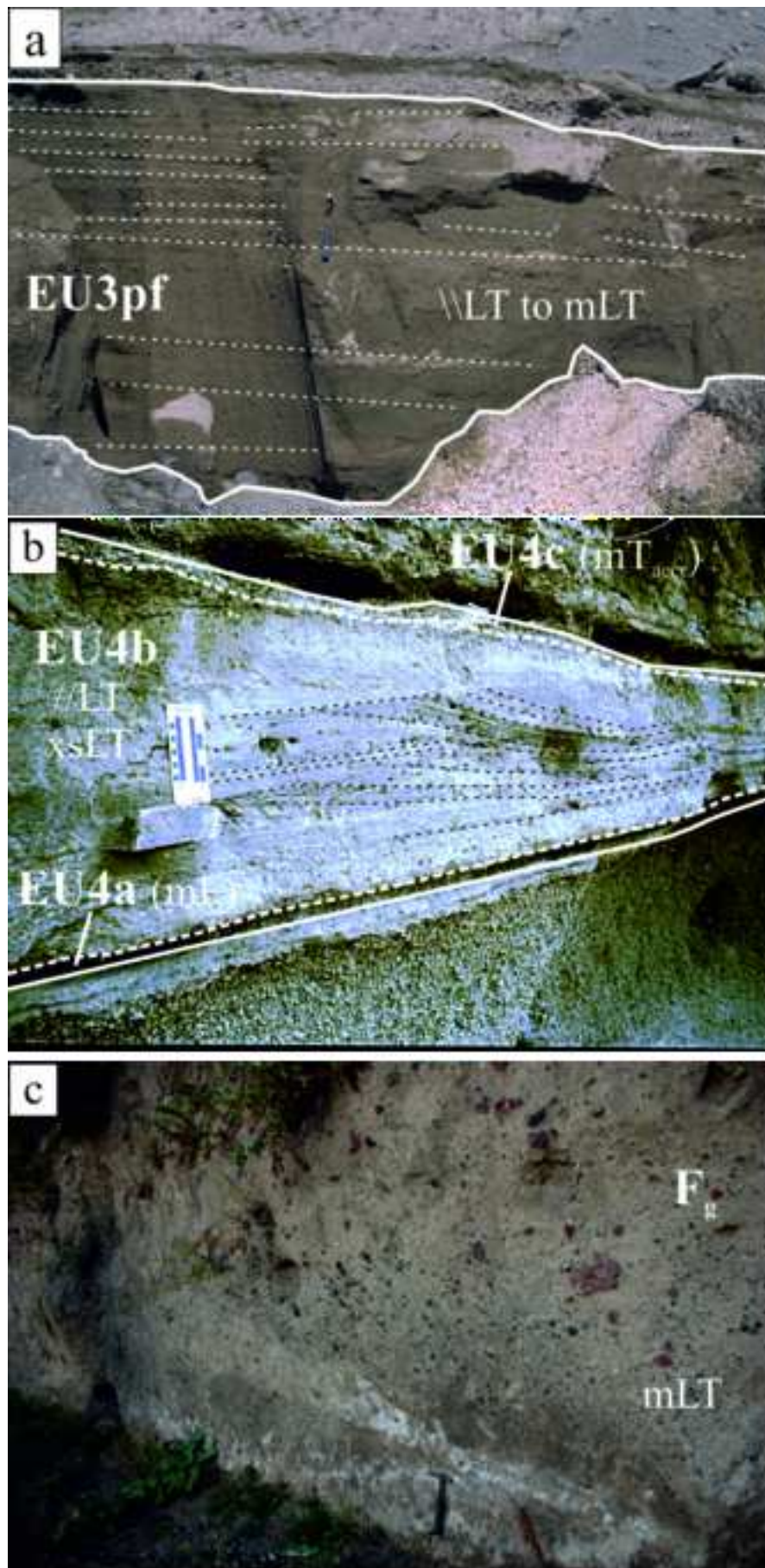
871 **Table 6** Volume estimations for the “Cupa Fontana” and “Cupa Olivella” PDC lobes of the F<sub>g</sub> unit using methods CRs,  
872 (VOR) and TIN.

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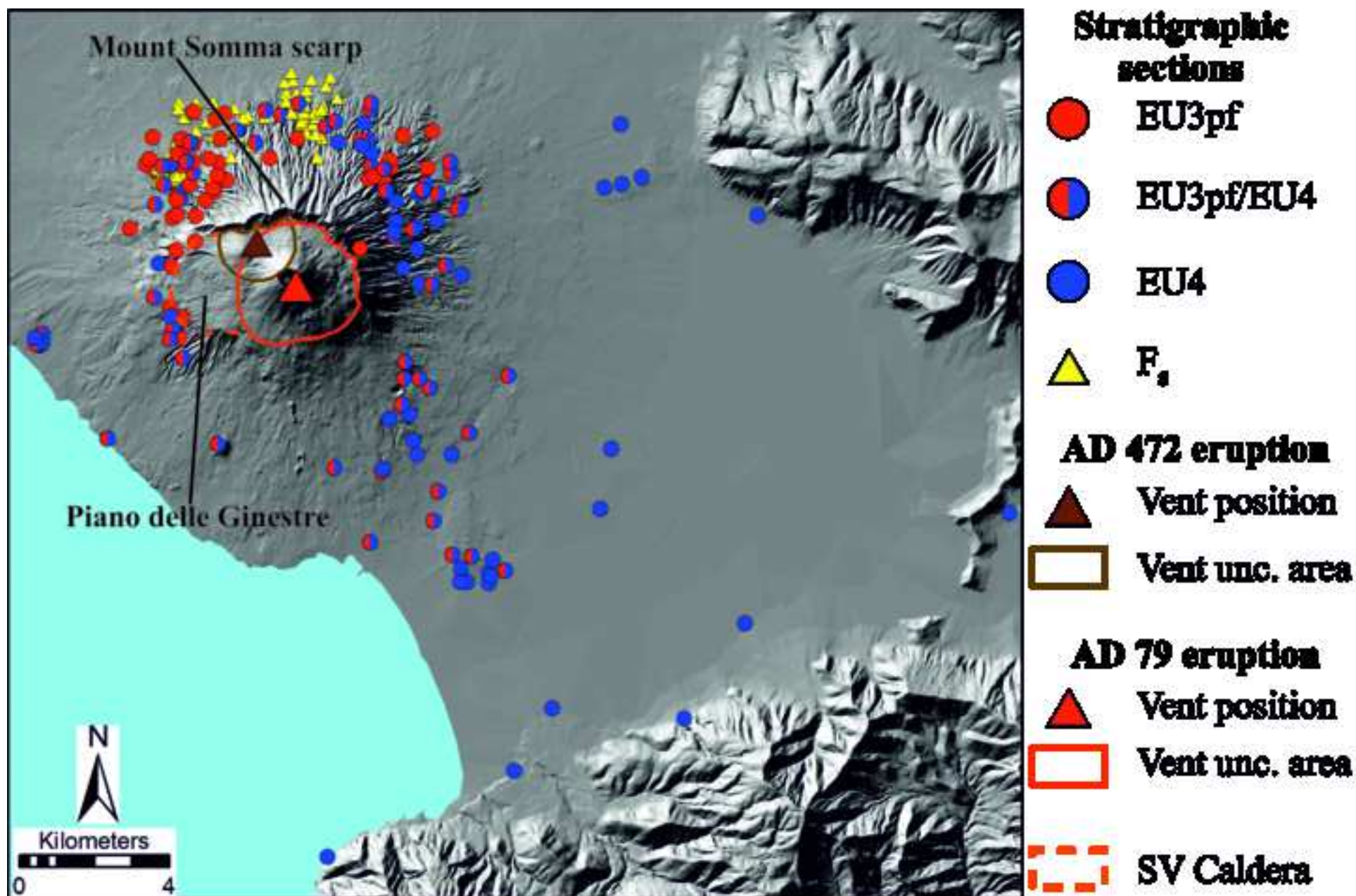
874 **Table 7** Summary of data used for TGSD estimations for all the studied units. The uncertainty on deposit density is related  
875 to the standard deviation of the data.



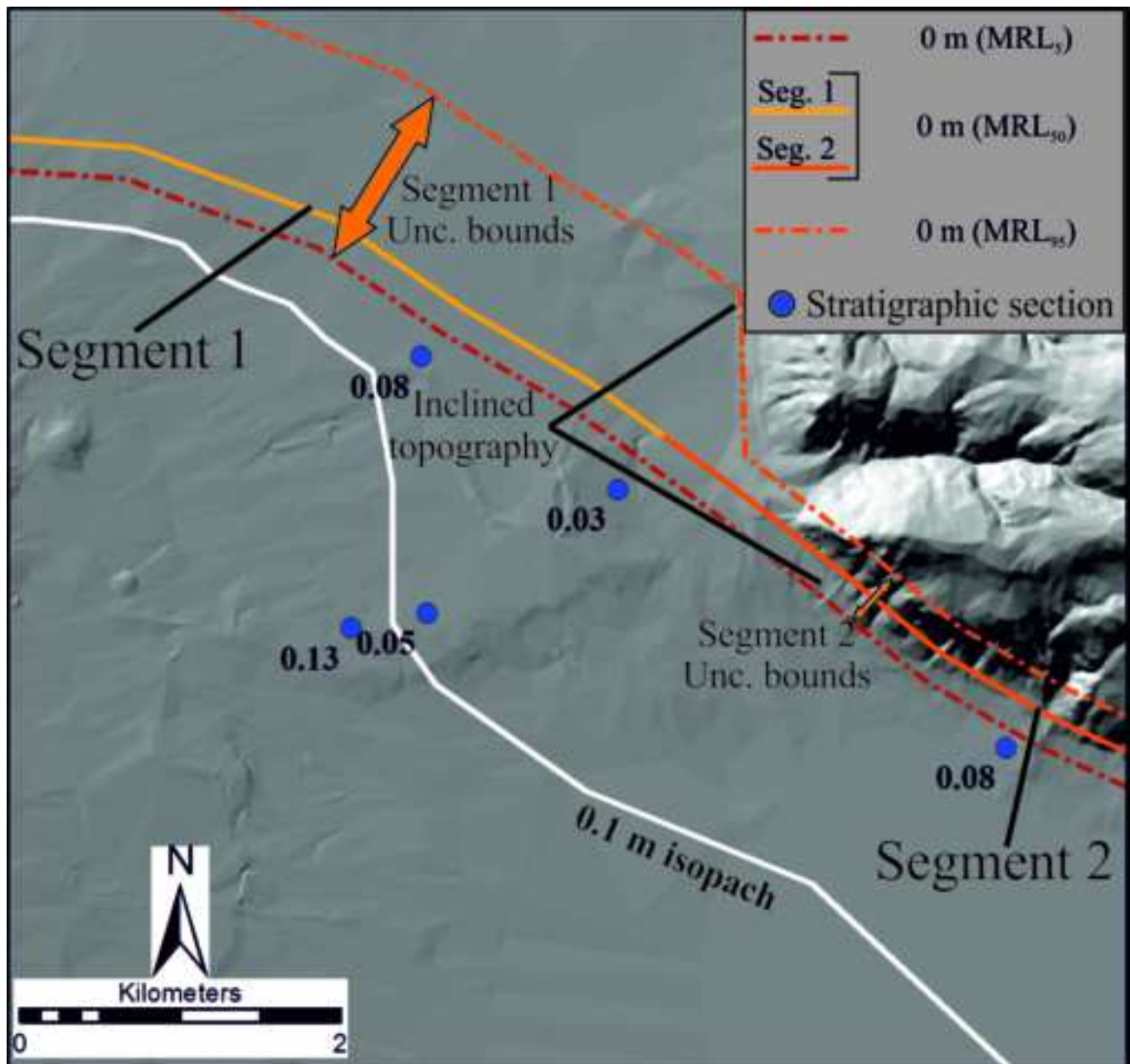
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**Figure 3 stratigraphic sections used to calculate the parameters of the EU3pf, EU4 and F<sub>s</sub> (Cupa Olivella and Cupa Fontana lobes) units. Vent positions, vent uncertainty areas and Somma-Vesuvius caldera outline as defined in Tadini et al. (2017b).**



**Figure 4** example of the identification of two segments (Segment 1 in light orange and Segment 2 in dark orange) for the MRL<sub>30</sub> of the EU4b unit. Starting from these two segments (and from the others that compose the whole outline), different uncertainty bounds are traced according to the amount and quality of the constraints available (inclined topography, proximity and thickness of stratigraphic sections, isopach lines).

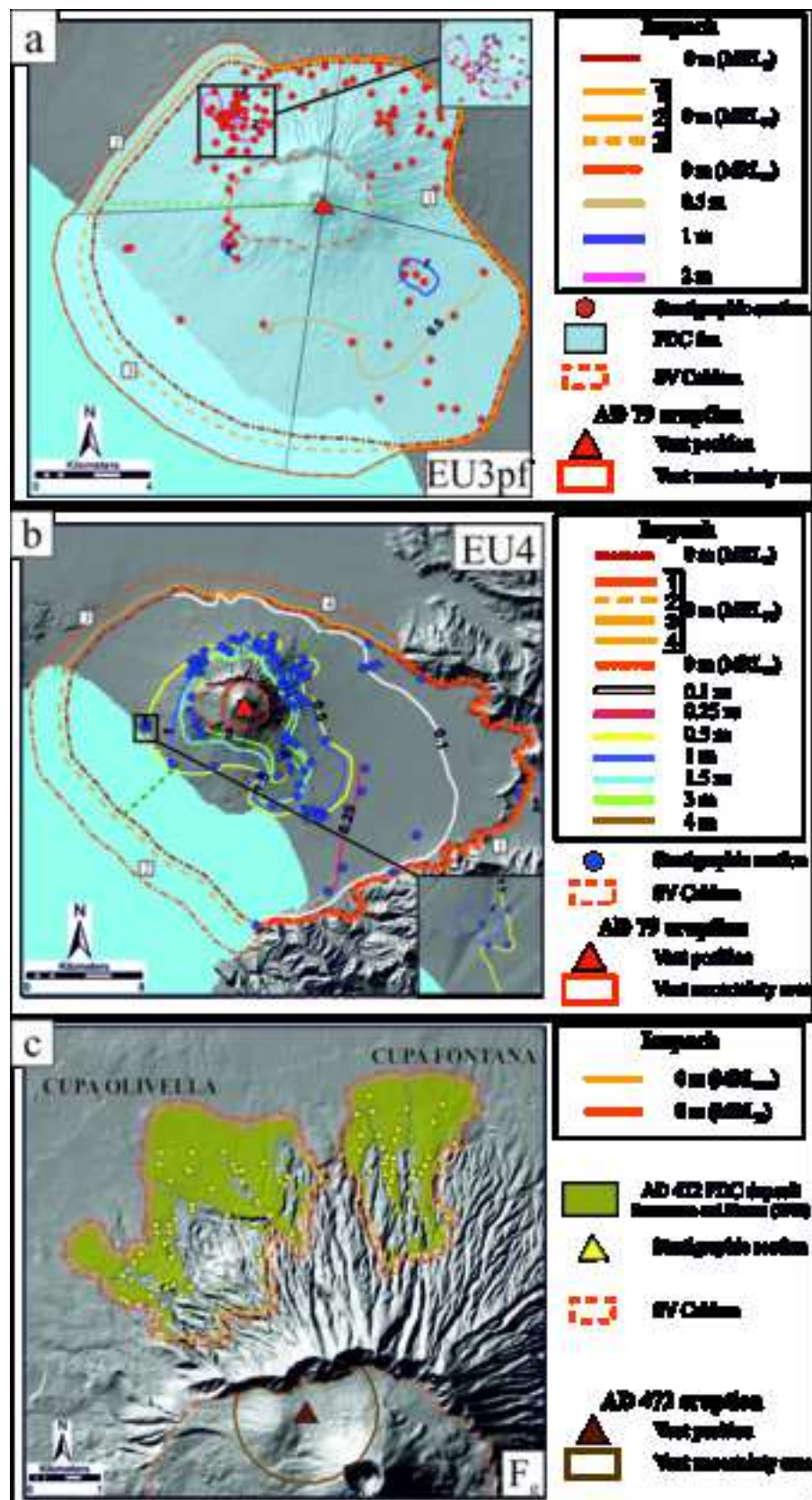


Figure 5 a) MERL outline and isopachs related to the EU3pf unit. The green dashed line identifies the north and south sectors used for volume and TGED calculations; b) MERL outline and isopachs related to the EU4 unit. The dark green dashed line identifies the NW and SE sectors used for volume and TGED calculations; c) MERL outline related to the F, Cupa Fontana and Cupa Olivella lakes. Preserved FDC deposits related to the AD 472 eruption (Bianchini and Sbrana 2019) are also shown. Vent positions, vent uncertainty areas and Bianchini-Mazzoni caldera outline as defined in Toffi et al. (2017c).

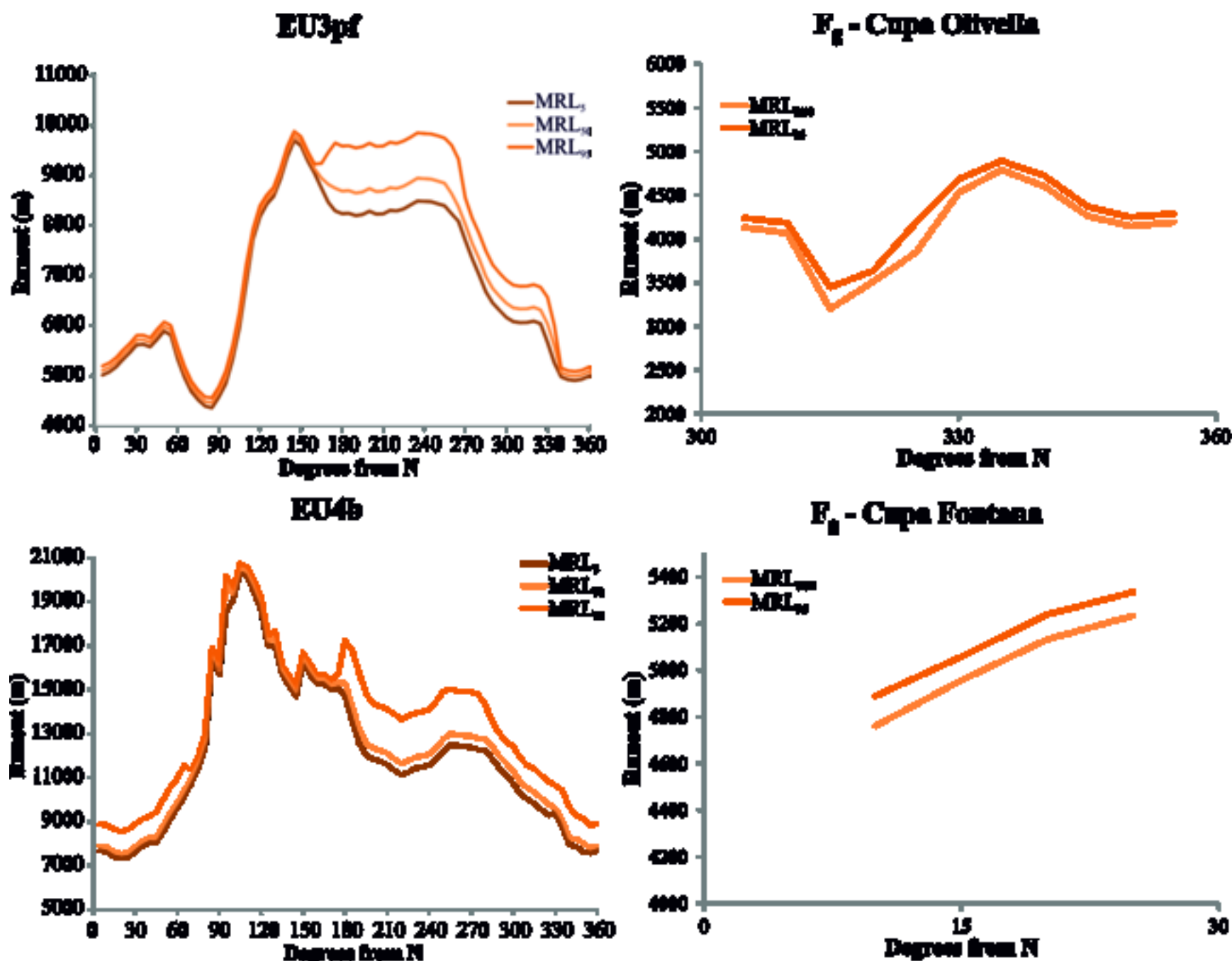
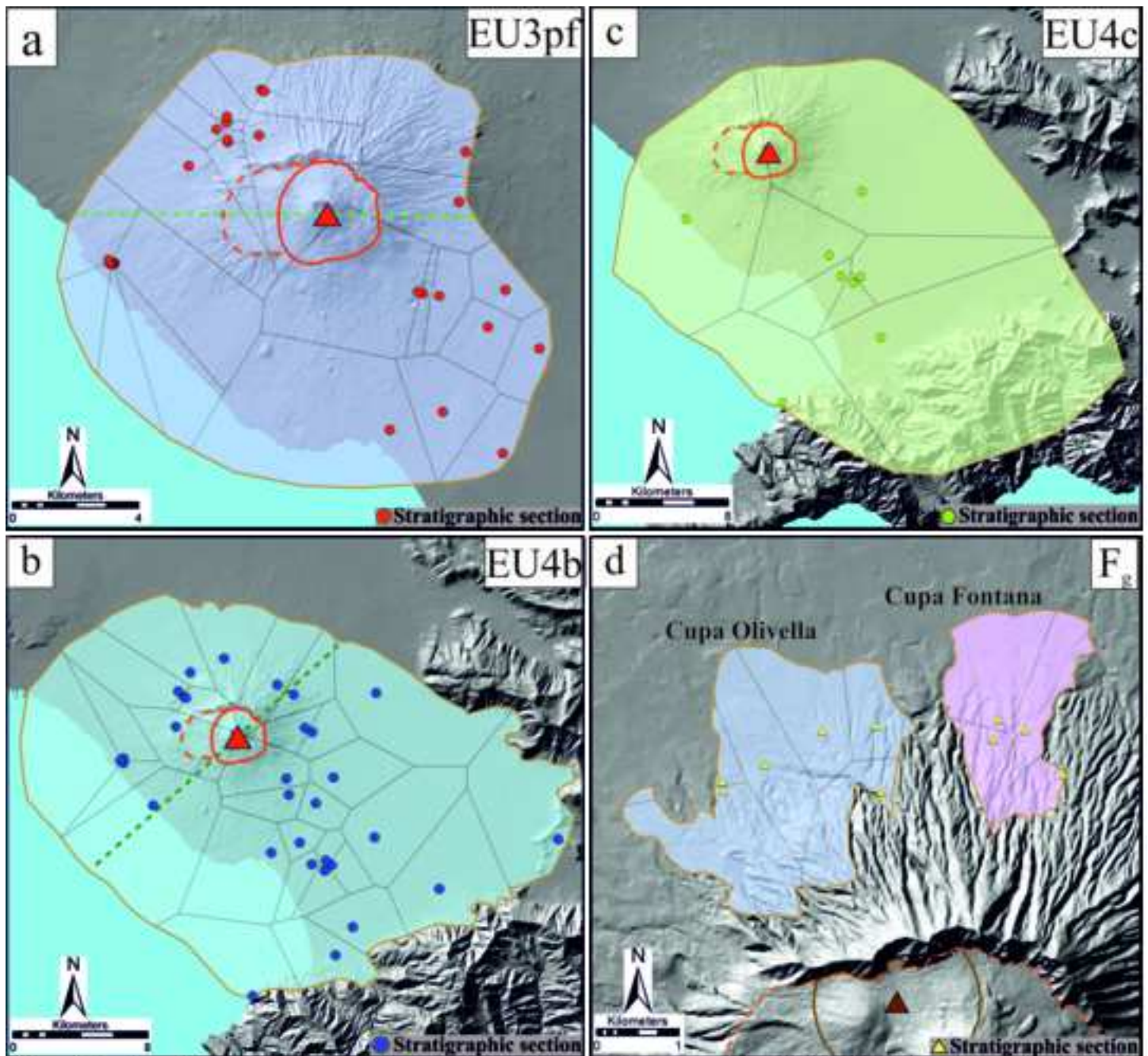
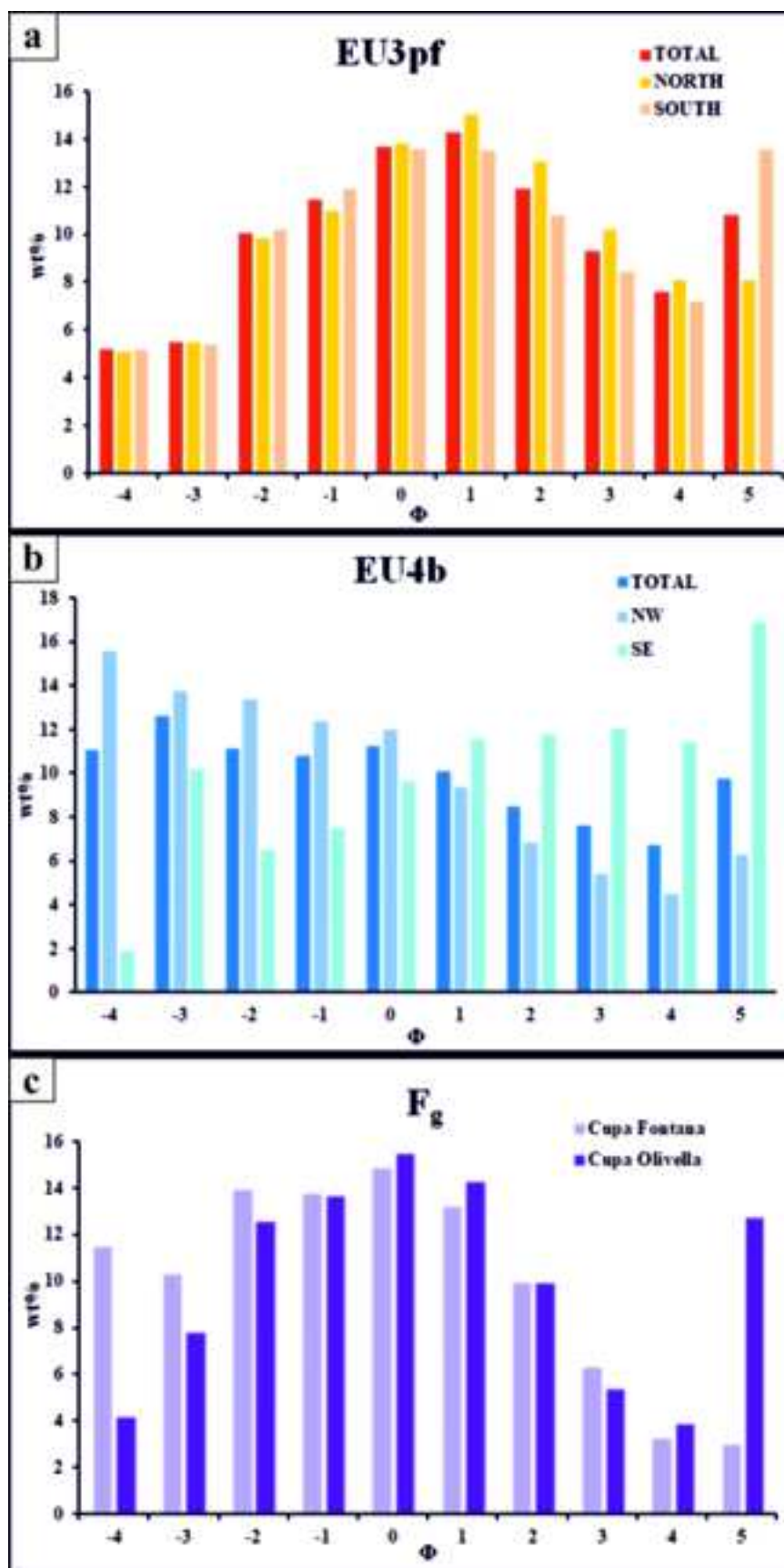


Figure 6 MRL outlines for the EU3pf and EU4b units and for the F<sub>8</sub> Cupa Olivella and Cupa Fontana lobes as a function of the angle (in degree) from the North (in clockwise direction).

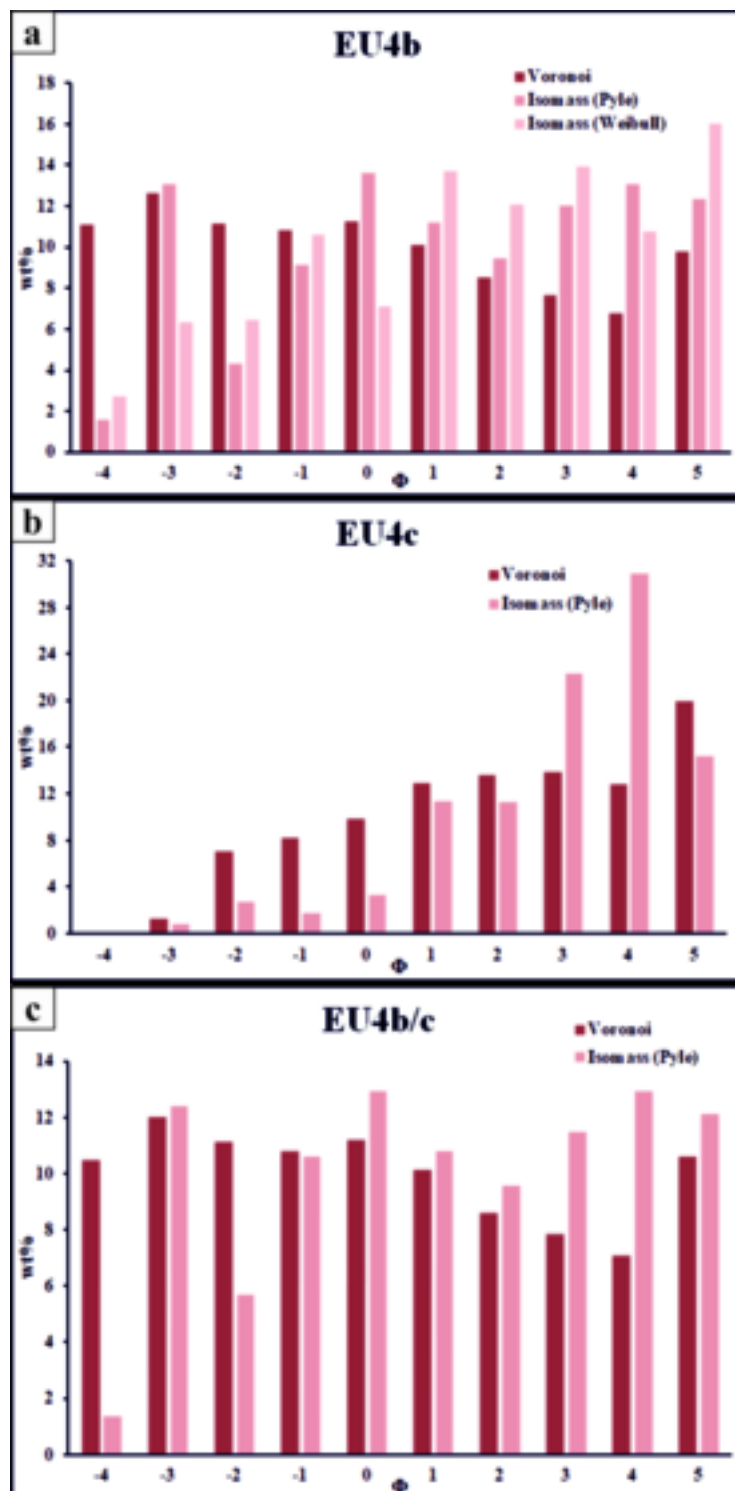




**Figure 7** stratigraphic sections with samples and related Voronoi polygons used to calculate the TGSD of the: a) EU3pf unit. The green dashed line identifies the north and south sectors used for TGSD calculations; b) EU4b unit. The dark green dashed line identifies the NW and SE sectors used for TGSD calculations; c) EU4c unit; d) F<sub>g</sub> (Cupa Olivella and Cupa Fontana lobes) unit. Vent positions, vent uncertainty areas and Somma-Vesuvius caldera outlines as defined in Tuffari et al. (2017b).



**Figure 8** TGSD calculated by using the Voronoi tessellation method for the a) EU3pf (Total, North and South sectors), b) EU4b (Total, NW and SE sectors) and c)  $F_g$  (Cupa Olivella and Cupa Fontana lobes) units.



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Table 1

UNIT	MIA (km <sup>2</sup> )		
	5 <sup>th</sup>	50 <sup>th</sup>	95 <sup>th</sup>
EU3pf	143	<b>166</b>	212
EU4b	492	<b>521</b>	610
F <sub>g</sub> CO	-	<b>4.8</b>	5.7
F <sub>g</sub> CF	-	<b>7.1</b>	8.1

Table 2

METHOD NAME	DESCRIPTION	UNITS FOR WHICH IT HAS BEEN USED	REFERENCE(S)
CRh	Partitioning of the deposit into homogeneous areas (PDC fans). Average value of thickness applied to the whole partition, whose volume is thickness*area. Total volume is the sum of the volumes of each partition.	EU3pf	Crandell (1989)
CRs	Similar to the above, but here defining areas or sectors in terms of topographic slopes, using the increments 0-15, 15-30, and >30 degrees.	EU3pf; EU4b; F <sub>g</sub>	Crandell (1989)
TR	Dispersal area of the deposits is reported on isopach maps and each of them is plotted in a <i>thickness vs. area diagram</i> ; the resulting best fit curve is then integrated up to the 0-m thickness isopach.	EU4b	Fierstein and Nathenson (1992)
PY	Dispersal area of the deposits is reported on isopach maps and each of them plotted in a <i>ln thickness versus square root area diagram</i> ; the resulting best fit curve is then integrated up to the 0-m thickness isopach.	EU4b	Pyle (1989)
VOR	Partitioning (using a nearest-neighbor algorithm) of the study area in as many polygons as the number of stratigraphic sections, each polygon having the thickness measured in the corresponding data point. Total volume is the sum of the product of the area of each cell by its thickness. The 0-m thickness isopach used is the MRL <sub>50</sub> .	EU3pf; EU4b; F <sub>g</sub>	Voronoi (1908) Bonadonna and Houghton (2005)
TIN	Vector surface method that consists of a network of triangles formed by connecting nodes (measured thicknesses at vertexes) according to the Delaunay criterion. Thickness in each point of the triangles is calculated through linear interpolation between the data at their vertexes.	EU3pf; EU4b; F <sub>g</sub>	Lee and Schachter (1980) Bisson and Del Carlo (2013)

Table 3

<b>UNIT</b>	<b>SLOPE CLASSES (°)</b>	<b>% MIA 50<sup>th</sup></b>	<b>N° SECTIONS</b>	<b>AVERAGE THICKNESS (m)</b>
EU3pf	0-15	77	62	1.94
	15-30	16.2	33	1.63
	>30	6.8	11	1.37
EU4b	0-15	89.9	69	1.25
	15-30	7.2	31	1.2
	>30	2.9	2	1.39
F <sub>g</sub> Cupa Olivella	0-15	67.9	24	4.11
	15-30	23.2	5	2.7
	>30	8.9	1	2
F <sub>g</sub> Cupa Fontana	0-15	73.7	22	1.63
	15-30	21.8	5	1.7
	>30	4.5	-	-

Table 4


Method	Unit	Sector	MRL	Volume (km <sup>3</sup> )
CRh	EU3pf	Total	MRL <sub>50</sub>	<b>0.265</b>
CRs	EU3pf	Total	MRL <sub>50</sub>	<b>0.267</b>
	EU4b			<b>0.507</b>
	Fg CF			<b>0.0053</b>
	Fg CO			<b>0.0234</b>
TR	EU4b	Total	MRL <sub>50</sub>	<b>0.364</b>
PY	EU4b	Total	MRL <sub>50</sub>	<b>0.334</b>
VOR	EU3pf	Total	MRL <sub>50</sub>	<b>0.281</b>
	EU4b			<b>0.560</b>
	Fg CF			<b>0.0034</b>
	Fg CO			<b>0.0215</b>
TIN	EU3pf	North	MRL <sub>5</sub>	0.089
			MRL <sub>50</sub>	<b>0.096</b>
			MRL <sub>95</sub>	0.100
		South	MRL <sub>5</sub>	0.086
			MRL <sub>50</sub>	<b>0.092</b>
			MRL <sub>95</sub>	0.111
	Total	MRL <sub>5</sub>	0.175	
	MRL <sub>50</sub>	<b>0.188</b>		
	MRL <sub>95</sub>	0.211		
	EU4b	NW	MRL <sub>5</sub>	0.119
			MRL <sub>50</sub>	<b>0.12</b>
		SE	MRL <sub>5</sub>	0.175
			MRL <sub>50</sub>	<b>0.175</b>
	Total	MRL <sub>5</sub>	0.179	
MRL <sub>50</sub>		<b>0.175</b>		
MRL <sub>95</sub>	0.292			
MRL <sub>50</sub>	<b>0.295</b>			
MRL <sub>95</sub>	0.313			
EU4c	Total	-	0.034	
Fg CF	Total	MRL <sub>5/50</sub>	<b>0.0026</b>	
		MRL <sub>95</sub>	0.0029	
Fg CO	Total	MRL <sub>5/50</sub>	<b>0.0121</b>	
		MRL <sub>95</sub>	0.0142	

Table 5


<b>Unit</b>	<b>Method(s) used for TGSD</b>	<b>Stratigraphic sections considered for TGSD</b>	<b>Samples used for TGSD</b>	<b>Samples used for deposit density</b>
EU3pf	Voronoi	27	98	17
EU4b	Voronoi Isomass	31	68	18
EU4c	Voronoi Isomass	8	8	2
F <sub>g</sub> Cupa Fontana	Voronoi	4	4	18
F <sub>g</sub> Cupa Olivella	Voronoi	6	6	2

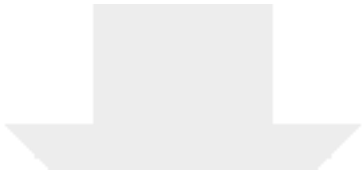


<b>Deposit density (kg/m<sup>3</sup>)</b>
1120 ± 250
1308 ± 171
1336 ± 85
1676 ± 96
1195 ± 97

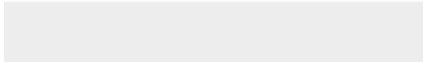



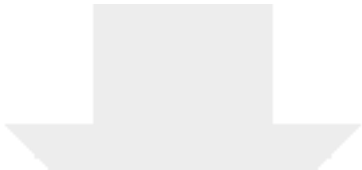
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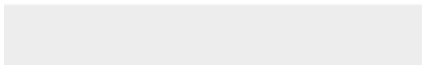
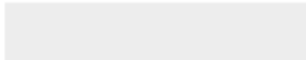


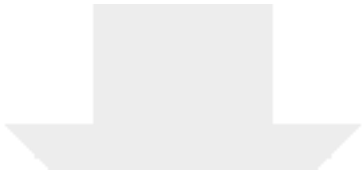
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