

1 **The volume of the 39.8 ka Campanian Ignimbrite, Italy**

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10 **Key Points**

- 11 • The preserved extra-caldera bulk volume of the ignimbrite is $61.5 \text{ km}^3 \pm 5.5 \text{ km}^3$.
- 12 • The eruption had a total volume of $164.9 \text{ km}^3 - 247.7 \text{ km}^3$ DRE and a magnitude of 7.7.
- 13 • The volume is essential for climate simulations of Europe during the Pleistocene.

14

15 **Abstract**

16 The 39.8 ka Campanian Ignimbrite (CI) is the largest caldera-forming eruption of the Campi Flegrei during
17 the Quaternary, which had a global-scale impact on the environment and human populations. The cooling
18 following the eruption and the several effects of it strongly affected the paleoenvironment and the migration
19 of hominids in Europe. The volume of the eruption is necessary to constrain the climate model of this area in
20 the past. However, despite a large number of studies, the Dense Rock Equivalent (DRE) volume estimates
21 range from 60 to 300 km^3 . Here we present a review of the previous volume evaluations and a new calculation
22 of the volume of the ignimbrite. This estimate is constrained by an isopach map that reconstructs the paleo-
23 topography during the eruption. The preserved total bulk extra-caldera volume of the ignimbrite is estimated
24 at $61.5 \text{ km}^3 \pm 5.5 \text{ km}^3$. The total PDC deposit volume is then corrected for erosion, ash elutriation, the

25 intracaldera deposit volume and the volume of tephra deposited in the sea. The total final volume estimate of
26 the eruption ranges from 164.9 km³ – 247.7 km³ DRE. This value corresponds to a mass of 4.30 - 6.46 x 10¹⁴
27 kg, a magnitude (M) of 7.7 and a VEI of 7. This M makes the CI the largest-magnitude Quaternary eruption
28 in the Mediterranean area. The new detailed estimation of CI eruption physical parameters confirms this event
29 as capable of having significantly affected human activity and the environment on a large scale at the time of
30 the eruption.

31

32 **Plain Language Summary**

33 The Campanian Ignimbrite is the most powerful eruption of Campi Flegrei, Italy, occurred around 40,000 of
34 years ago. It developed a huge pyroclastic density current, a flow of ash, rocks and gas at elevated temperature
35 and velocity, the most dangerous process related to volcanic eruptions. The rocks generated by the flow (the
36 ignimbrite) are located far from the caldera (up to 80 km), indicating the high energy of the eruption. In this
37 work, the thickness of this ignimbrite is reported on an isopach map, which helps to calculate the volume of
38 the ignimbrite and to understand the processes related to the flow. We estimate the volume of the magma of
39 the eruption (from 164.9 km³ to 247.7 km³) and the total mass of magma (4.30 - 6.46 x 10¹⁴ kg), correspond
40 of around 80 million of Olympic-size swimming pools and the weight of 102 billion of elephants. We classify
41 this eruption as a Volcanic Explosive Index of 7 on a maximum of 8, which defines it as the largest eruption
42 occurred in the Mediterranean area in the past. The volume is also important to model the climate impact of
43 this natural disaster that affected the human population of that time.

44

45 **Index Terms**

46 8428 Explosive volcanism (4302); 8408 Volcano/climate interactions (1605, 3309, 4321); 8414 Eruption
47 mechanisms and flow emplacement; 8486 Field relationships (1090, 3690); 8404 Volcanoclastic deposits.

48 **Keywords**

49 Campanian Ignimbrite; Campi Flegrei; Isopach maps; Ignimbrite volumes; Pyroclastic density currents; Super-
50 eruption.

52 **1. Introduction**

53 Pyroclastic density currents (PDCs) have large impacts on human communities and the environment; they can
54 cause catastrophic environmental and property damage and loss of life, as well as accounting for the major
55 proportion of deaths caused by volcanic activity. In the last 200 years, 26.8% of volcano-induced mortality
56 resulted from PDCs (Tanguy et al., 1998; Witham, 2005). Moreover, global and regional climatic effects can
57 result from the injection of ash and sulfur aerosols into the stratosphere during large explosive eruptions,
58 leading to a “volcanic winter” (Rampino and Self, 1992; Stuiver et al., 1995; Thordarson and Self, 1996). The
59 quantitative computation of the size of explosive eruptions is essential to understand their potential impact on
60 humans, climate and ecosystems (Mason et al., 2004). Calculating the volume of volcanic large eruptions is
61 necessary to define the size and to model the climate effects of these natural phenomena occurred in the past.

62 The total eruptive product of large caldera-forming eruptions can consist of both fall deposits and ignimbrites
63 (Parfitt & Wilson, 2008), and typically the largest proportion is transported in PDCs and emplaced as
64 ignimbrites. Numerical models have greatly improved estimates of tephra dispersal from the fallout phase in
65 recent years (Barsotti et al., 2008; Bonadonna et al., 1998, 2005; Bonadonna & Phillips, 2003; Costa et al.,
66 2006, 2012; Folch, 2012; Folch et al., 2010). However, at present, a clear “reference” method for the
67 calculation of ignimbrite volume does not exist and uncertainties on such computations are huge (Mason et
68 al., 2004). The volume of ignimbrites is difficult to evaluate due to the irregularity of the ignimbrite surface,
69 the variable thickness (controlled by the paleomorphology), the effect of erosion, the presence of younger
70 products and the variable density of the deposits.

71 The Campanian Ignimbrite (CI; Barberi et al., 1978; De Vivo et al., 2001; Fedele et al., 2008; Fisher et al.,
72 1993) is associated with the most powerful caldera-forming eruption from Campi Flegrei (Fig. 1a) (Rosi &
73 Sbrana, 1987; Perrotta et al., 2006; Scarpati et al., 2013), which occurred at 39.8 ka (Giaccio et al., 2017). It is
74 one of the largest late Quaternary explosive events and has been considered as an example of a super-eruption
75 (Sparks et al., 2005). The CI tephra represents the most widespread volcanic deposit and one of the most
76 important temporal/stratigraphic markers for the Early Upper Paleolithic of western Eurasia (F. G. Fedele et
77 al., 2003; Giaccio et al., 2008; Pyle et al., 2006). The eruption may have affected human residents in different

78 ways: by destroying the animal and human populations, by altering the species composition and growth rhythm
79 and by changing the availability of water (F. G. Fedele et al., 2002, 2007; Lowe et al., 2012). The abrupt
80 volcanic cooling following the eruption occurred in a more intense way in Eastern Europe and Northern Asia,
81 and reached from -6°C up to -9°C. The cooling could have influenced the migration of the populations and
82 have affected the daily life for Neanderthals and modern humans during the Middle to Upper Paleolithic
83 transition (Black et al., 2015; Marti et al., 2016).

84 In this work, we present a review of all papers that determined the CI volume. Despite the large number of
85 studies, the estimates of total Dense Rock Equivalent (DRE) volume of CI range from 60 to 300 km³, with no
86 apparent convergence on an accepted value (Civetta et al., 1997; Cornell et al., 1983; Costa et al., 2012; F. G.
87 Fedele et al., 2003; Fisher et al., 1993; Giaccio, 2006; Marianelli et al., 2006; Marti et al., 2016; Pappalardo et
88 al., 2008; Perrotta & Scarpati, 2003; Pyle et al., 2006; Rolandi et al., 2003; Rosi et al., 1983, 1999; Scarpati et
89 al., 2014; Thunell et al., 1979). The volume of distal tephra (both Plinian and co-ignimbrite) is well defined
90 due to the many measurements across the vast region and a recent improvement of computational methods
91 (Costa et al., 2012; Marti et al., 2016). Nevertheless, the volume of the PDC deposits was never calculated by
92 direct measurements. We propose a rigorous method to develop the isopach map of the Campanian Ignimbrite
93 based on mapping of the preserved deposits and the reconstruction of the paleomorphology, especially in
94 mountain areas. We provide a revised volume of the pyroclastic density current extra-caldera deposits of the
95 CI preserved on land based on a verifiable method of calculation. Using this as a base, we correct for erosion,
96 elutriation, intracaldera volume and underwater deposits to calculate the most reliable total bulk and Dense
97 Rock Equivalent (DRE) volumes for this eruption. The obtained volume strongly reduces the total error in the
98 previous estimates, which should be used to better develop and constrain the climate model of the Eastern
99 Europe during the Paleolithic period.

100

101 **2. Volcanological background**

102 The activity in the Campi Flegrei began prior to 80 ka (Pappalardo et al., 1999; Scarpati et al., 2013). The area
103 consists of two nested depressions formed and activated during both the CI and the more recent ~15 ka
104 Neapolitan Yellow Tuff (NYT) eruptions (Acocella, 2008; Orsi et al., 1996; Perrotta et al., 2006; Vitale &

105 Isaia, 2014; Di Vito et al., 1999). A recent study identified an M 6.6 event correlated to the Y-3 tephra, named
106 Masseria del Monte Tuff; this eruption is likely to have generated a caldera collapse between CI and NYT
107 (Albert et al., 2019). After the NYT eruption, intra-caldera volcanic activity continued with more than 70
108 eruptions, subdivided into three volcanic epochs: epoch I (15-10.6 ka), epoch II (9.8-9.2 ka) and epoch III (4.6-
109 3.8 ka) (Isaia et al., 2009; Smith et al., 2011; Di Vito et al., 1999). The last eruption occurred in 1538 CE and
110 led to the formation of the Monte Nuovo tuff cone.

111 The CI eruption emplaced both pyroclastic fall and PDC deposits in a complex sequence currently exposed in
112 proximal, medial, distal and ultra-distal outcrops (Fig. 1) (Barberi et al., 1978; Cappelletti et al., 2003; Engwell
113 et al., 2014; L. Fedele et al., 2008; Fisher et al., 1993; Orsi et al., 1996; Perrotta et al., 2006; Perrotta & Scarpati,
114 1994, 2003; Rosi et al., 1988, 1996, 1999; Scarpati et al., 2015a, 2015b; Scarpati & Perrotta, 2016; Smith et
115 al., 2016; Sparice, 2015; De Vivo et al., 2001). The first phase of the eruption generated a Plinian column up
116 to 44 km high (Marti et al., 2016; Rosi et al., 1999), producing a widespread fall deposit dispersed by winds
117 to the east (Marti et al., 2016; Perrotta & Scarpati, 2003; Rosi et al., 1999; Scarpati & Perrotta, 2016). A
118 pyroclastic density current then spread over an area of 7,000 km² and surmounted ridges more than 1,000 m
119 high (Barberi et al., 1978; Fisher et al., 1993). This stage caused the caldera collapse and the accumulation of
120 lithic breccia's deposits (Breccia Museo) in scattered outcrops along the caldera rim (L. Fedele et al., 2008;
121 Melluso et al., 1995; Perrotta & Scarpati, 1994; Rosi et al., 1996). In distal outcrops, most of the CI is
122 represented by a massive, gray ignimbrite (Barberi et al., 1978; Fisher et al., 1993; Scarpati et al., 2015a;
123 Scarpati & Perrotta, 2012). In more distal and ultra-distal sites deposits are made up by coarse to fine ash
124 containing both co-plinian and co-ignimbrite tephra (Engwell et al., 2014; Smith et al., 2016; Sparks & Huang,
125 1980; Thunell et al., 1979). The tephra marker related to this eruption is essential to correlate volcanological
126 and archeological sites in the Mediterranean area and Eastern Europe. Tephra-based correlations of human
127 sites were used to date the Middle to Upper Paleolithic transition (Lowe et al., 2012).

128 The complex stratigraphy of this eruption differs between proximal and distal outcrops (Fig. 1b, Fig. 1c).
129 Moreover, it is difficult to study the lateral correlations due to the absence of outcrops in medial areas (except
130 for the Lago di Patria outcrop, Table A2 in Data Repository), because all quarry-pits have been refilled. The
131 limited drill core data shows little evidence of lateral unit change. In our study, we refer to the stratigraphic
132 units proposed by Fedele et al. (2008) (proximal area) and Cappelletti et al. (2003) (medial and distal areas).

133 The stratigraphy in proximal areas, from bottom to top, consists of 6 units: 1) Plinian pumice fallout deposit
134 (PPF); 2) unconsolidated stratified ash flow (USAF); 3) welded gray ignimbrite (WGI) interlayered with some
135 more welded levels (Piperno); 4) lower pumice flow unit (LPFU); lithic breccia unit (BU), in places with
136 welded spatter beds (SU); and 6) upper pumice flow unit (UPFU). The stratigraphic sequence of distal outcrops
137 involves, from bottom to top: 1) PPF; 2) USAF; 3) WGI; 4) lithified yellow tuff (LYT); and 5) coarse pumice
138 flow (CPF).

139 **3. The previous estimates of the CI volume**

140 Define the eruptive volume is necessary to simulate the climate impact of this eruption in Eastern Europe. Here
141 is reported a review of the previous estimates of the CI volume aim to define a constrained volume for this
142 eruption.

143 The total volume erupted during a caldera-forming eruption, like the CI, is composed of the mass ejected
144 during the phases that produced Plinian columns (V_{pf}), and pyroclastic density currents (V_{pdc}) (1):

$$145 \quad V = V_{pf} + V_{pdc} \quad [\text{eq. 1}]$$

146 Both V_{pf} and V_{pdc} are made of the main primary deposits (respectively the Plinian fallout V_{ppf} and the ignimbrite
147 V_i) and their associated co-plinian fall (V_{cpf}) and co-ignimbrite ash fall (V_{ci}). Consequently (2):

$$148 \quad V = V_{ppf} + V_{cpf} + V_i + V_{ci} \quad [\text{Eq. 2}]$$

149 All these four factors were calculated during the last forty years by different authors and with different methods
150 (Table 1), resulting in final dense rock equivalent (DRE) volume estimates ranging from 60 to 300 km³ (Civetta
151 et al., 1997; Cornell et al., 1983; Costa et al., 2012; F. G. Fedele et al., 2003; Fisher et al., 1993; Giaccio, 2006;
152 Marianelli et al., 2006; Marti et al., 2016; Pappalardo et al., 2008; Perrotta & Scarpati, 2003; Pyle et al., 2006;
153 Rolandi et al., 2003; Rosi et al., 1983, 1999; Scarpati et al., 2014; Thunell et al., 1979).

154 Due to the difficulty to distinguish the contribution of the co-plinian fall and the co-ignimbrite ash fall in ultra-
155 distal locations, some authors simply refer to the widespread Y-5 ash layer, which comprises both. This layer
156 is the tephra marker linked to the CI eruption and is recognized from marine cores across the Eastern
157 Mediterranean region to Russia, for this reason, Y-5 is an excellent chronostratigraphic marker in the Northern
158 Hemisphere (Cornell et al., 1983; Engwell et al., 2014; F. G. Fedele et al., 2003; Giaccio et al., 2006; Narcisi

159 & Vezzoli, 1999; Pyle et al., 2006; Smith et al., 2016; Thunell et al., 1979; Ton-That et al., 2001). Previous
160 studies distinguished also the co-plinian and co-ignimbrite contribution (Marti et al., 2016; Perrotta & Scarpati,
161 2003; Smith et al., 2016; Sparks & Huang, 1980); some of them calculated the relative volume and the
162 associated method of calculation will be discussed later (Marti et al., 2016; Perrotta & Scarpati, 2003).

163 The first volume estimate of the ignimbrite was presented by Thunell et al. (1979). Based on a geometrical
164 method that considers a covered area of over 6000 km² with a thickness up to 100 m and assuming a radial
165 flow of the PDC, they estimate the DRE volume is at least 30-40 km³. The DRE volume of the Y-5 ash layer
166 within the 1-cm isopach contour was also estimated at 30-40 km³ (65 km³ bulk) and the authors recognized
167 that Y-5 is composed by a co-plinian and a co-ignimbrite ash, but they did not calculate each contribution to
168 the volume. Their total DRE volume is 60-80 km³ for the eruption.

169 Cornell et al. (1983) calculated the ash-fall layer volume of Y-5 from an isopach map derived by different
170 cores drilled in the Mediterranean Sea (73 km³ bulk). They then included the ignimbrite DRE volume proposed
171 by Thunell et al. (1979) in their overall eruption volume estimate.

172 Fisher et al. (1993) estimated a bulk volume of the original pyroclastic current of about 500 km³ by
173 circumscribing a circle of deposits with a radius of 100 km, 100 m thick at the center that thinned to zero at
174 the perimeter of the circle.

175 Civetta et al. (1997) is one of the first works that subdivided the volume of the CI based on the pumice
176 composition. The authors divided the magma into three different types: a most evolved one that consists of
177 Plinian fallout and some ignimbrite up to 50 km from the vent (a volume of 25 km³ DRE), a magma with
178 intermediate composition that includes some of the ignimbrite out to its farthest extent (100 km³ DRE), and a
179 least-evolved magma that includes much of the ignimbrite in the Campanian Plain (20 km³ DRE). All the
180 volume calculations were made by circumscribing circles with a radius similar to the maximum distance
181 reached from the vent by that magma type and a thickness that goes from the maximum thickness of ignimbrite
182 of that composition at the caldera center to zero at the perimeter of the circle.

183 Pappalardo et al. (2008) used petrological data to constrain the pre-eruptive magma storage dynamics and, in
184 agreement with Civetta et al. (1997), proposed a total volume of 200 km³ DRE (20 km³ for the fallout and 180
185 km³ for the ignimbrite).

186 Rosi et al. (1999) calculated the bulk volume of the Plinian fallout as 15 km³ based on the method proposed
187 by Pyle (1989), which assumes exponential thickness decay away from the vent and an elliptical isopach
188 distribution with the source at one focus; in the CI case, this focus corresponds to a central vent, located in the
189 Campi Flegrei caldera center (town of Pozzuoli). The same technique was used by Perrotta and Scarpati (2003),
190 who estimated a bulk volume of 4.03 km³, the different value being the result of a different way than Rosi et
191 al. (1999) used to trace the isopach lines. In the same work, the authors attempt, for the first time, to
192 discriminate between the co-plinian and co-ignimbrite components. The coarse ash of ultra-distal deposits was
193 interpreted as the co-plinian phase, while the fine ash represents the co-ignimbrite component. The authors
194 evaluated the thicknesses of the two parts and estimated the volume as follows: 16 km³ of co-plinian ash and
195 100 km³ of co-ignimbrite ash. Scarpati and Perrotta (2016) subdivided the fallout into five layers (A to E) and
196 calculated the volumes for each of them using the same exponential fitting, obtaining a primary fallout of 5.33
197 km³ (0.88 km³ DRE) and a co-plinian ash of 14.67 km³ (6.88 km³ DRE).

198 These analyses were improved upon by Pyle et al. (2006), who estimated the minimum bulk volume of the CI
199 fallout of 74 km³ or 31 km³ DRE: the authors used the general observation that many fallout deposits show
200 exponential decay of thickness (Pyle, 1989) and formulated that the total volume of the exponentially thinning
201 sheet is equal to $13.08T_0b_t^2$ (T_0 is the maximum thickness at source and b_t is the linear distance over which the
202 isopach thickness falls by a half). In the same work, the authors compared these results with a second approach
203 based on the rate of thinning of the distal ash sheets (Pyle, 1989, 1990): given that the thickest ash layer in
204 marine cores is of the order of 10–20 cm, it is most likely that the total bulk ash volume associated with the
205 eruption was in the range 74–120 km³ (31–50 km³ DRE) (Pyle et al., 2006).

206 A first attempt to compare all the volume estimates was proposed by Fedele et al. (2003), who considered the
207 sum of the conservative estimates reported in literature. The total DRE volume they proposed is 200 km³ (the
208 sum of the fallout, the PDC deposits and the Y-5 ash layer volumes (Civetta et al., 1997; Rosi et al., 1999;
209 Thunell et al., 1979)).

210 Giaccio (2006) calculated the volume of the PDC using a complex truncated cone, with a concave surface and
211 variable heights: 70 m up to 10 km from the center, 50 m up to 20 km, 20 m up to 45 km and 0 m up to 100
212 km. The volume obtained is 385 km³ (215 km³ DRE). At the same time, he proposed a revised isopach map

213 for the fallout deposits, resulting in a volume estimate of 10 km³ (3 km³ DRE). Moreover, combining all
214 available data on the distal tephra of CI from the literature (Castagnoli et al., 1995; Cornell et al., 1983; McCoy
215 & Cornell, 1990; Melekestsev et al., 1984; Narcisi & Vezzoli, 1999; Paterne et al., 1986; Seymour &
216 Christanis, 1995; Seymour et al., 2004; Ton-That et al., 2001; Upton et al., 2002), Giaccio (2006) calculated
217 the volume of this fraction as 180 km³ (86 km³ DRE). He thus estimated a bulk volume of 575 km³ (300 km³
218 DRE).

219 The most difficult part of drawing isopach maps of the Plinian fallout is the limited number of distal subaerial
220 locations where the tephra is found. To solve this, a new volume estimate was proposed by Costa et al. (2012)
221 based on the fit of an advection – diffusion tephra dispersion model to thickness data. They obtained a bulk
222 volume of the tephra of 250-300 km³ (104-125 km³ DRE) and a total volume of the eruption of 430-680 km³
223 (180-280 km³ DRE).

224 An innovative method for estimating the PDC volume was used by Scarpati et al. (2014). They applied
225 equation (3) to calculate the ignimbrite volume assuming a co-ignimbrite volume (V_{ci}) of 100 km³ obtained by
226 Perrotta and Scarpati (2003) and a mean vitric loss of 0.65. The method is based on the enrichment factor of
227 Walker (1972, 1980) and the vitric loss of the ignimbrite proposed by Sparks and Walker (1977). The volume
228 (V) (3) is equal to:

$$229 \quad V = V_{ci}/\text{vitric loss} - V_{ci} \quad [\text{Eq. 3}]$$

230 The bulk volume of the PDC deposits thus estimated is 54 km³ (25 km³ DRE). In the same study, the authors
231 proposed a review of the previous volume estimations (Scarpati et al., 2014).

232 The most recent work on the fallout volume was presented by Marti et al. (2016). The authors recognized two
233 distinct plume phases: the Plinian and the co-ignimbrite fall. They applied a computational inversion method
234 that explicitly accounts for the two phases and for gravitational spreading of the umbrella cloud. The Plinian
235 fallout bulk volume thus calculated is 54 km³ (22.6 km³ DRE) and the co-ignimbrite bulk volume is 153.9 km³
236 (61.6 km³ DRE), for a bulk total volume of 207.9 km³ (84.2 km³ DRE).

237 To summarize, the existing estimates of the total DRE volume of the CI eruption range from 60 to 300 km³
238 (Civetta et al., 1997; Cornell et al., 1983; Costa et al., 2012; F. G. Fedele et al., 2003; Fisher et al., 1993;

239 Giaccio, 2006; Marianelli et al., 2006; Marti et al., 2016; Pappalardo et al., 2008; Perrotta & Scarpati, 2003;
240 Pyle et al., 2006; Rolandi et al., 2003; Rosi et al., 1983, 1999; Scarpati et al., 2014; Thunell et al., 1979) and
241 those for the bulk volume of the CI pyroclastic density current deposits range between 54 and 500 km³ (Civetta
242 et al., 1997; Cornell et al., 1983; Fisher et al., 1993; Marianelli et al., 2006; Pappalardo et al., 2008; Rolandi
243 et al., 2003; Scarpati et al., 2014; Thunell et al., 1979). The margin of error in these volumes is unacceptably
244 high due to the different methods used, especially in view of the relevance of such figures on the impact on
245 climate and the environment. While the computational methods for the fallout deposits have improved
246 significantly in the past ten years and the related figures for the fallout phase appear strong and solidly based
247 on field data (Costa et al., 2012; Marti et al., 2016), the volume figures for the CI ignimbrite appear to remain
248 very poorly constrained, although this volume largely affects the estimation of the volume of elutriated co-
249 ignimbrite ash, which is the dominant fallout phase across Europe and the most relevant fraction of ash injected
250 into the stratosphere at the time of the eruption (e.g. Costa et al., 2018).

251

252 **4. The making of the CI isopach map**

253 In order to reduce this wide range in volume estimates, we focus on constraining the volume of the PDC
254 deposits of the CI. Our calculation of thickness and volume does not take into account the initial pyroclastic
255 Plinian fall phase and the co-ignimbrite fallout; we used the fall volume calculation of other authors, the
256 maximum and the minimum proposed in literature by Perrotta and Scarpati (2003) and Marti et al. (2016). Our
257 CI isopach map is based on previous published data, fieldwork and the assessment of the paleo-topographic
258 control exerted on the deposits thickness distribution.

259

260 *4.1 Database and fieldwork*

261 Published data regarding CI thickness and outcrop locations were collected from 42 papers (presented in Data
262 Repository, Table 1). The whole data were inserted in a GIS Open-Source QGIS 3.4
263 (<https://www.qgis.org/it/site/>) database including 238 localized outcrops. The database includes the name of
264 the location, the lithological description, the geographic coordinates, the elevation a.s.l., the thickness of the
265 flow units (specifying whether total or outcrop thickness), the maximum lithic dimensions and the degree of

266 welding. Where both base and top of the CI are exposed, the thickness is classified as total and elsewhere it is
267 considered a minimum thickness.

268 This database has been augmented by our field data acquired in 97 locations (presented in Data Repository,
269 Table 2), both in proximal and distal areas (Fig. 1d). Fieldwork was aimed to measure the total or minimum
270 thickness, the local stratigraphy and to understand the relation of the ignimbrite with the topography.

271

272 *4.2 The zero-thickness isopach*

273 The zero-thickness isopach is an outer limit beyond which the CI is not present, and it delimits the current
274 areal distribution of the PDC outcrops. The isopach was reconstructed through a first phase of revision of the
275 geological maps already existing at the scale 1:10,000, 1:50,000 or 1:100,000 (ISPRA, 2009, 2010, 2011a,
276 2011b, 2011c, 2011d, 2014a, 2014b, 2016, 2018; Rosi & Sbrana, 1987; Sbrana & Toccaceli, 2011; Servizio
277 Geologico d'Italia, 1963, 1965a, 1965b, 1965c, 1966, 1967a, 1967b, 1971a, 1971b, 1975; Vezzoli & Barberi,
278 1988). The contact was traced between the CI and older units and extrapolated where CI does not crop out. In
279 this circumstance, the ignimbrite is generally covered by younger deposits, but it is necessary to assess if the
280 CI was never emplaced there. To distinguish between these two cases, a statistical and morphological analysis
281 of the actual slope of the top of the CI was applied and a comparison between the topography and the average
282 slope of the CI top was carried out. Where the slope angle is comparable, the area was included in the zero-
283 thickness isopach, even if CI is not cropping out. Greater slope angles were attributed to underlying basement
284 (mostly Meso-Cenozoic calcareous or flysch) and the isopach was traced to leave out these areas and no
285 primary CI deposition was interpreted.

286

287 *4.3 The isopachs*

288 To determine the isopach locations, two different methods were used, one in the proximal area (from the
289 caldera to the base of the Apennine Mountains, including the Campanian Plain) and one in the more distal
290 area. The almost complete lack of outcrops in the Campanian Plain and the valley-ponded depositional style
291 in the ridge-valley topography of the Apennine Mountains (L. Fedele et al., 2016; Langella et al., 2013; Perrotta

292 et al., 2010; Rosi et al., 1983, 1996; Scarpati et al., 2014, 2015a; Sparice, 2015) make these different
293 approaches necessary.

294 In the proximal area, data from the literature (Bellucci, 1994; ISPRA, 2011d; Milia and Torrente, 2007;
295 Ortolani and Aprile, 1985; Rolandi et al., 2003; Scandone et al., 1991; Torrente et al., 2010), consisting of
296 more than 300 thickness values of CI from boreholes, outcrops and geological sections were used to fit
297 isopachs on the map. In the distal area, the isopach locations were based upon our field observations and the
298 reconstruction of the pre-CI topography (Fig. 2). A series of profiles in the Apennine Mountains were drawn
299 to outline the trend of the valleys (Fig. 2b). The coast-line in Mediterranean Sea at the time of the CI
300 emplacement (39.8 ka) was lower than present-day, but it is difficult to define the precise level due to the high
301 tectonic activity in the region and the difference in behavior between a closed basin such as the Mediterranean
302 Sea and the Atlantic Ocean, which responded predictably to global sea-level changes. Based upon limited sea-
303 level correlation work in the Mediterranean basin (Antonioli, 2012; Antonioli et al., 2004; Lambeck & Bard,
304 2000), we assumed a sea level between 75 m and 87 m lower than present-day.

305 Topographic cross-sections were traced orthogonally to the center of the valley and to the contour lines,
306 including the flanks of the reliefs and the zero-thickness isopach. The slopes of the valley above the CI zero
307 isopach were extended and gradually shallowed toward the valley center in order to reconstruct the paleo-
308 valley with an inclination of the sides similar to the current slope, always taking into consideration the
309 geological and morphological features (Fig. 2c), and assuming that the Meso-Cenozoic mountain slopes have
310 not significantly changed since 40 ka. The CI typically has a valley-pond geometry inside the Apennine
311 Mountains (L. Fedele et al., 2016; Perrotta et al., 2010; Rosi et al., 1996; Scarpati et al., 2014, 2015a; Sparice,
312 2015). The base elevation of the paleo-valleys is constrained by field data where the CI base has been
313 measured.

314 These reconstructed valleys culminate generally in a V shape, with the bottom elevation, above the sea level,
315 for each profile representing the paleo-valley floor. All these elevations represent the ancient pattern of the
316 valley bottom, for this reason, they were modified if they were inconsistent with the progressive downslope
317 decrease in elevation. We also took into account the slope of the present-day drainage network (Fig. 2a).

318 Finally, the neo-incision of rivers in the profiles was flattened, to not include in the result the linear erosion of
319 the last 39.8 ka (Fig. 2c). The CI thickness is calculated by these modified profiles, and it is always constrained
320 by field data on the CI thickness and with the geological maps. These thickness values are then reported on
321 the isopach map.

322 All the isopachs were traced always in coherence with field data, for both thickness and base elevation, geology
323 of Meso-Cenozoic sides of the valleys and, finally, the progressive downslope decrease in the base elevation
324 of the valleys referred to the present-day drainage network. Where these data were not consistent, an
325 adjustment in some profiles was necessary. The most significant adjustments were made for a resulting over-
326 thickening inside the valleys. In these cases, the thickness was modified in coherence with fieldwork.

327

328 **5. Results**

329 We use, as starting point for the volume estimation, the PDC volume, obtained from the detailed isopach map.
330 From the previous review, it is evident that this information lacks in previous works on the CI volume. Here,
331 we refer to all PDC units of the CI, that in the medial and distal outcrops are mainly composed by WGI. Density
332 and porosity data are used to define the DRE volume.

333

334 *5.1 The isopach maps*

335 The statistical and morphological analysis of the upper surface of the CI used 48804 points throughout the
336 areal extension of the deposits (both in proximal and distal areas). This analysis shows that 64% (31057) of
337 the points have slopes lower than 5°. Moreover, 80% of the points have slopes lower than 10° and 99% have
338 a surface slope lower than 55° (Fig. 3). This is in agreement with the observation on the slope of the top surface
339 of the valley-ponded Taupo Ignimbrite, which is around 8° (Wilson & Walker, 1985).

340 Based on these results, the 0-m isopach was traced to enclose all the mapped CI and areas that probably have
341 the CI below the recent sedimentary cover and have a slope less than 15°. The total area enclosed by the 0-m
342 isopach of the CI is 3216 km² (Fig. 4). To understand also the total area of the region involved in the PDC, a

343 shape was drawn comprising all the areal extension of the isopach 0-m. The enveloped area is equal to 7547
344 km², similar to the 7000 km² estimate (Barberi et al., 1978).

345 The isopach map traced in the proximal area does not include the intracaldera deposits. The maximum
346 thickness in proximal areas is 80 m (Fig. 5), mainly based on outcrops near the caldera rim; the CI thins
347 gradually away from the caldera margin. Two areas of thickening are identified just north of the caldera and
348 east of Lago Patria (up to 70 m) and in the area of Casoria (up to 50 m) (Fig. 6a). Three main areas of thinning
349 (down to 10 m) are recognized to the north in the Campanian Plain (Fig. 6b), in the area between Aversa and
350 Acerra and in the south of the Campanian Plain (Fig. 6a).

351 Two thickened portions are on the northern side of the Campanian Plain (north-east of Mondragone) (Fig. 6b)
352 and on the eastern side (from Caserta to Maddaloni) (Fig. 6c), both just in front of the first Apennine ridges.

353 The isopach for the distal reaches has a maximum thickness of 50 m in the area of Maddaloni Valley (Fig. 6c).
354 A series of confined valleys show local thickening. These include, from northwest to southeast, Mortola (up
355 to 30 m), Roccamonfina (up to 30 m) (Fig. 6d), San Lorenzello and all the Volturno plain (up to 20 m) (Fig.
356 6e), Sant'Agata dei Goti (up to 40 m), Tufara (up to 20 m), Monteforte Irpino and Avellino (up to 30 m) (Fig.
357 6f), Tramonti (up to 10 m) and Sorrento (up to 20 m) (Fig. 6g).

358

359 *5.2 Density of the CI deposits*

360 More than 40 samples from different outcrops scattered around the Campanian Plain were analyzed to
361 determine their density. Samples were cut in cylinders (with radius between 0.9 cm and 2 cm and height
362 between 0.8 and 5.7 cm) or cubes (sides from 0.8 to 2.5 cm) and analyzed using a Micromeritics AccuPyc II
363 1340 helium pycnometer. The resulting density was used to interpret total and open porosity, the density is
364 used to determine the DRE volume.

365 The bulk density (ρ) of the WGI samples from the Campanian Plain ranges from 0.745 ± 0.015 g/cm³ to 1.330
366 ± 0.003 g/cm³, with an average at 0.980 ± 0.011 g/cm³. The bulk density of the Piperno unit ranges from 1.275
367 ± 0.008 g/cm³ to 1.302 ± 0.002 g/cm³, with an average of 1.287 ± 0.004 g/cm³ (presented in Data Repository,
368 Table 3). Open porosity was estimated with geometric (V_g) and matrix volume (V_m): $100 \cdot (V_g - V_m) / V_g$, while
369 closed porosity was determined using the DRE of the WGI and Piperno powder, which was obtained by the

370 pycnometer. The total WGI porosity (ϕ_t) was calculated directly adding up closed and open porosity and it
371 ranges from $49 \pm 5\%$ and $71 \pm 5\%$ and the average is $61.6\% \pm 5\%$, for the Piperno unit it is $50 \pm 1\%$. The ρ
372 DRE is $2.6077 \pm 0.0031 \text{ g/cm}^3$. The DRE volume is determined multiplying the bulk volume by $(100 - \phi_t)/100$.

373

374 *5.3 Deposits volume calculation*

375 The area enclosed by each isopach, reported in Fig. 7, allows the CI volume to be calculated. This is the
376 subtended area of the plot thickness-cumulative area (Walker, 1980, 1981); the area of each isopach was
377 calculated directly from the QGIS software. Table 2 displays the values of the area and the volume for each
378 isopach. The largest part of the volume is relative to deposits thicknesses $<10 \text{ m}$ (60.52%), whereas the
379 isopachs from 40 m to 80 m contain less of the 10% of the total volume (7.17%).

380 The total volume of the preserved extra-caldera CI deposits on land is $61.5 \text{ km}^3 \pm 5.5 \text{ km}^3$ ($22.0 \pm 2.2 \text{ km}^3$
381 DRE).

382 To understand the extra-caldera volume subdivision in proximal and distal areas, the isopach map is portioned
383 in two parts, one comprising all the Campanian Plain, and the other from the first Apennine ridges to the final
384 runout (Fig. 5). The resulting extra-caldera volumes are $46.4 \pm 1.6 \text{ km}^3$ in the proximal area ($\sim 75\%$) and 15.1
385 $\pm 3.9 \text{ km}^3$ in the distal area ($\sim 25\%$); the sources of error and the uncertainties are due to the methods used and
386 their calculation is explained in Supporting Information.

387 A recent study proposed contour maps of the lower and the upper surfaces of the CI for the north-western
388 sector of the proximal area, based on 1000 of lithostratigraphic logs from boreholes (Ruberti et al., 2020). The
389 difference of the upper surface and the lower one is the CI thickness, which is not reported on the work of
390 Ruberti et al. (2020). The extrapolated thicknesses from the maps were compared with the isopach map of the
391 proximal area of this work and it shown great similarities in the areas of Mondragone, Caserta and Lago Patria.
392 On the other hand, there are some differences of the thicknesses in the Volturno Plain, where the authors
393 suggest a thicker CI. To evaluate these discrepancies, a new proximal isopach map was drawn taking into
394 consideration the new thickness data. The volume related to this map is 46.7 km^3 , meaning a difference of 0.3
395 km^3 with the volume previously estimated. This value (0.3 km^3) is fully included in the 1.6 km^3 of error and
396 uncertainties in the proximal area. For this reason, the data proposed by Ruberti et al. (2020) were not inserted

397 in the isopach map reported in this work, however, a greater thickness in the Volturno Plain could be
398 considered, even though it doesn't change the final total volume of the proximal area and of all the CI.

399

400 **6. The volume of the Campanian Ignimbrite**

401 The preserved volume of the deposits of an eruption is the first essential datum to understand the magnitude
402 of the eruption itself. These data are generally very poorly constrained for very large explosive eruptions,
403 mainly due to the difficult to estimate the PDC volume deposits and the areal distribution of the very distal
404 tephra layers.

405 The CI PDC volume was only qualitative estimated while in this work we proposed a volume calculation of
406 the PDC deposits and consequently a more detailed determination of the CI magnitude based on the volume
407 calculation (Mason et al., 2004).

408

409 *6.1 Extracaldera volume*

410 Our quantitative evaluation of the CI extra-caldera bulk volume (V_{pr}), is $61.5 \text{ km}^3 \pm 5.5 \text{ km}^3$. However, this is
411 not the total volume of the CI PDC deposits, which depends upon several corrections that must be applied to
412 this value. A significant amount of pyroclastic material was deposited in the sea and within the caldera,
413 significant erosion has occurred in the last 39.8 ka, and a large amount of co-ignimbrite ash elutriated or rose
414 into the air as a column.

415 The reconstructed isopachs do not consider the linear erosion due to river incision of the CI so the possible
416 areal erosion must be calculated. The linear erosion is referred to the selective erosion due to rivers, while the
417 areal erosion comprises all the regional processes that occurred in the area. The deposits of WGI show a mainly
418 valley-ponded deposit pattern; in many areas where the ignimbrite was deposited in narrow valleys (for
419 instance near Roccamonfina), the only unit that mantles the topography is USAF, while the upper surface of
420 WGI is mainly horizontal (Fig. 3) (Sparice, 2015). This suggests that USAF is a facies emplaced in a wider
421 area distribution than WGI, comprising also topological highs with mantling features. The thickness of USAF
422 is mainly between 10 cm and 1 m and, in rare cases, it can reach 3 m (L. Fedele et al., 2016). A median

423 thickness of 1 m is assumed as eroded material for all the enveloped area (7547 km², projected area) not
424 covered by valley-pond facies, as a reference for the areal erosion. From a DEM, the real surface enveloped
425 area was computed at 9575 km², meaning the calculation of the area on the DEM and not on a projected
426 horizontal surface, it was so evaluated also the deposition on mountain slope (as a mantling feature deposition).
427 The volume associated with the areal erosion is 9.6 km³ (V_e) (3.7 km³ DRE, using the average density of WGI).
428 This is a correction based on field observation (USAF able to mantling the topography) and an average
429 calculation (the thickness and the area), obviously, it is just a reference value, and could vary if the eroded
430 thickness, or involved area, are considered substantially different.

431 The CF caldera is located near and below the current sea-level but, about 40 ka, the coastline was farther to
432 the west and south corresponding to a level between 75 and 87 m below its present position (Antonioli, 2012;
433 Antonioli et al., 2004; Lambeck & Bard, 2000) (Fig. 8). Based on the distribution on land of the ignimbrite,
434 safely assumed with a radial spreading (Fisher et al., 1993; Ort et al., 2003; Thunell et al., 1979), and the
435 position of the CF caldera relative to the coastline (Fig. 8) a roughly equal amount of material should be present
436 both on land and offshore (Barberi et al., 1978). Flow deposits of Kos and Krakatau demonstrate that PDC can
437 travel considerable distance above sea water (Allen & Cas, 2001; Carey et al., 1996; Dufek & Bergantz, 2007)
438 as well the Campanian PDC flowed over the water of the Bay of Naples to deposit on the Sorrento Peninsula
439 (~ 35 km from Pozzuoli Bay to Sorrento) (Fisher et al., 1993). As the PDC passed over the water, the more
440 dilute upper parts did not interact with the water while the denser undercurrent developed a sheared contact
441 with the water, leading to pyroclastic material entering the water and developing submarine currents (Dufek
442 et al., 2007).

443 The presence of the turbidity currents in the Mediterranean basin and coeval to the eruption was confirmed by
444 the analyses of the core CT85-5 in the Tyrrhenian Sea (40°19'02''N, 11°15'42''E) located more than 200 km
445 west from the CF caldera (Castagnoli et al., 1995; Giaccio, 2006; Giaccio et al., 2006; Hajdas et al., 2011).
446 The CI tephra recognized within the core was used as an important time marker and it is 45 cm thick. The
447 nearby CT85-6 confirmed the presence of the CI tephra, however, it was less studied as its record is shorter
448 and the CI is not reported fully (Hajdas et al., 2011). In the CI layer, were found shallow water gastropods and
449 internal lamination, which indicate that at least 10 cm of the section are from turbiditic origin (Castagnoli et
450 al., 1995; Giaccio, 2006; Hajdas et al., 2011). These volcanoclastic currents related to the CI eruption are

451 strongly reported in all the Tyrrhenian basin (Giaccio, 2006; McCoy & Cornell, 1990) interpreted as a large
452 syn-eruptive phenomena of the CI deposits, triggered by the PDCs which entered inside the water and in
453 general to the volcanic event. The turbidity currents can be reasonably considered as primary products of the
454 eruption (Giaccio, 2006).

455 For these reasons a large amount of underwater material is realistic and, because of the nearly equal radial area
456 covered by sea versus on land, is considered equal to the on-land material, so each is considered to have a
457 volume of $61.5 \text{ km}^3 \pm 5.5 \text{ km}^3 (V_m)$.

458

459 *6.2 Intracaldera volume*

460 Some deep wells were drilled in the 1940s and 1950s to understand the deep geothermal system in the Campi
461 Flegrei, reaching depths of 1600-3000 m below ground surface (Rosi & Sbrana, 1987). A well-developed
462 neogenic mineral zonation was observed with four main zones marked by distinctive mineral assemblages:
463 argillitic zone (down to ~700 m), illite-chlorite zone (down to ~1300 m), calc-aluminum silicate zone (down
464 to ~2300 m) and thermometamorphic zone (below ~2300 m). The temperatures reach high values of 360°C in
465 the calc-aluminum silicate zone (Rosi & Sbrana, 1987). These wells reached also the CI, but the extensive
466 hydrothermal alteration prevented its identification. Due to the high uncertainties of correlating CI deposits
467 inside the caldera, the isopach map was traced without the intracaldera area and the intracaldera volume was
468 not estimated in this work, which refers to literature data.

469 More recently, a 506 m drill-hole has been drilled western of Naples, reaching both NYT and CI (De Natale
470 et al., 2016; Mormone et al., 2015). The hydrothermal alteration in proximity of CI (around 439 and 501 m)
471 was recognized and made the correlation with the deposits extremely difficult. However, through lithological,
472 mineralogical and $^{40}\text{Ar}/^{39}\text{Ar}$ dating the authors recognized at least 250 m of intracaldera CI (De Natale et al.,
473 2016), this value was already observed through geological and geophysical features (Torrente et al., 2010).
474 The ignimbrite volume inside the caldera, which in this work has a dimension of 64 km^2 , was then estimated
475 less than 16 km^3 (De Natale et al., 2016).

476 From field observation and literature data (De Natale et al., 2016), there is no evidence of significant
477 intracaldera thickening. Therefore, a very large (~ 0.9) f value (the fraction of the total magma volume erupted
478 prior to the onset of collapse) is attributed to the CI eruption (Cashman & Giordano, 2014). Moreover, the ratio
479 between the measured collapses related to the NYT and CI is 2.5, a data that looks unreliable due to the much
480 larger volume of CI than the NYT (De Natale et al., 2016). The authors proposed two models: a vent outside
481 the Campi Flegrei caldera (model 1) and a very large regional uplift related to the CI eruption (model 2), that
482 seems realistic to explain the anomalous ratio, especially if a much smaller eruption as Monte Nuovo one (with
483 a volume less than 1 km^3 DRE (D'Orlando et al., 2005; Piochi et al., 2005)) produced an uplift of 5 to 8 m
484 (Capocci, 1835; Pescandola, 1947).

485 There are some uncertainties due to the caldera dimension, indeed, Vitale and Isaia (2014) proposed a
486 polygonal caldera 12 km wide, which corresponds to an area of 144 km^2 . Considering an average thickness of
487 250 m of intracalderic deposits (De Natale et al., 2016), and an area varying from 64 to 144 km^2 , the
488 intracaldera volume (V_{intr}) ranges between 16 km^3 to 43.2 km^3 ($7.9\text{-}21.4 \text{ km}^3$ DRE).

489

490 *6.3 Distal tephra volume*

491 The CI tephra is an important correlation tool and time marker mainly to relate the Quaternary stratigraphy in
492 different basins and archeological sites in the Western Eurasia. The tephra layer is visible in numerous
493 sedimentary records, including archeological (Anikovich et al., 2007; F. G. Fedele et al., 2003; Giaccio et al.,
494 2008; Kozłowski, 1998; Pyle et al., 2006), marine (Keller et al., 1978; Paterne et al., 1986, 1999; Ton-That et
495 al., 2001), and terrestrial sequences (Veres et al., 2013) as also cave-entrance environments (F. G. Fedele et
496 al., 2003; Giaccio et al., 2008) and lacustrine records (Narcisi, 1996). In very distal sites, it can be found as a
497 cryptotephra not visible to the naked eye, but clearly useful as an absolute and relative chronological and
498 stratigraphic marker (Lowe et al., 2012). The tephra it has been identified in the Mediterranean basin (Paterne
499 et al., 1986, 1999; Ton-That et al., 2001), in south-western Romania (Veres et al., 2013), in Italy (e.g.
500 Monticchio, Fedele et al. 2002, 2003; Giaccio et al. 2008; Narcisi 1996), in Eastern Europe and Russia
501 (Anikovich et al., 2007; Pyle et al., 2006), in Greece (Kozłowski, 1998), in Ukraine (Melekestev et al. 1984)
502 and in Bulgaria (Bluszcz et al. 1992; Paterne 1992).

503 Define the distribution of the ultra-distal deposits is a difficult task due to the limitation of the field data
504 available and to the thinning of the ash layers, affected by a large erosion. Underestimation of the deposit
505 volume can be derived by simple extrapolation from proximal, medial and distal data to the ultra-distal region.
506 Reconstructing the tephra dispersion and volume of a volcanic eruption is fundamental to understand the
507 impact on climate, humans and ecosystems. The case of the CI is complicated by the presence of both co-
508 plinian ash and co-ignimbrite ash due to the large-volume pyroclastic flow that generate a co-ignimbrite plume
509 (Woods, 1998; Woods & Wohletz, 1991), both transported far away from the vent up to eastern Europe and
510 Russia (Cornell et al., 1983; Engwell et al., 2014; F. G. Fedele et al., 2003; Giaccio et al., 2006; Narcisi &
511 Vezzoli, 1999; Pyle et al., 2006; Smith et al., 2016; Thunell et al., 1979; Ton-That et al., 2001).

512 The contribution of the co-plinian and co-ignimbrite phases to the tephra layer was not an object of study in
513 this work. However, attempt the ultra-distal tephra volume is necessary to define the total CI eruptive volume.
514 Different authors in the past used various techniques both to define the tephra partitioning volume and to
515 distinguish the two phases in the ash layer (Engwell et al., 2014; Marti et al., 2016; Perrotta & Scarpati, 2003;
516 Smith et al., 2016; Sparks & Huang, 1980).

517 Sparks and Huang (1980) recognized the bimodal grain-size of the ultra-distal deposits of the CI, where the
518 coarse lower unit is formed during the plinian phase, while the finer unit at the top corresponds to the co-
519 ignimbrite phase. The authors estimated that the fine layer represents, on average, the 65% of the tephra
520 volume, which increases away from the vent, from 20% at 450 km distance up to 95% of the deposit at 1660
521 km from the vent. However, an absolute volume for each phase was not defined. The decreasing of Plinian
522 material with distance from the source was also observed by Engwell et al. (2014), who used the grain-size
523 data to investigate the dispersal of the co-plinian and the co-ignimbrite phases. The authors calculated that 40
524 $\pm 5\%$ of the volume of tephra within 850 km of the vent is related to the Plinian phase. Furthermore, they
525 recognized the difficult to quantify the absolute volume of the two phases.

526 The first work that attributed a volume to the two components was presented by Perrotta and Scarpati (2003).
527 The method used by the authors was previously explained. At a later time, Marti et al. (2016) modelled the CI
528 tephra dispersion and gave a volume estimation of the two phases. They recognized the great impacts of the
529 tephra fallout in the westward migration of modern hominid groups in Europe. Moreover, they supported the

530 hypothesis that Neanderthals populations persisted in southern Europe after the CI eruption, especially in
531 southern Iberia (Zilhão, 2006).

532 Smith et al. (2016) used the CI tephra glass composition to map the dispersal of the Plinian and the co-
533 ignimbrite components over the dispersal region. This method is substantially crucial to recognize the CI in
534 the ultra-distal region. In an especial way, it is essential to correlate this important chronological marker in
535 archeological sites and to investigate spatio-temporal variability in climate change and the timing of human
536 cultural events in eastern and central Europe (F. G. Fedele et al., 2003, 2008; L. Fedele et al., 2008; Lowe et
537 al., 2012). Based on the glass composition, the authors recognized that the PDC component is dominant in the
538 ultra-distal deposits, and the PDC produced the most voluminous deposits of the eruption.

539

540 *6.4 The volume, mass and magnitude of the CI*

541 As we said in the previous paragraph, a great part of the pyroclastic current was elutriated or rose into the air
542 as a column during the eruption and dispersed to the east (Cornell et al., 1983; Engwell et al., 2014; Perrotta
543 & Scarpati, 2003; Pyle et al., 2006; Scarpati & Perrotta, 2016; Thunell et al., 1979). The co-ignimbrite phase
544 resulted as a substantial part of the total volume; however, it remains difficult to define the associated absolute
545 volume instead of a percentage of the tephra layer.

546 The ignimbrite volume (V_i) (4 and 5) without the co-ignimbrite phase can be estimated as follows:

$$547 \quad V_{imin} = V_{pr} + V_m + V_{intr} + 2V_e = 56 + 56 + 16 + 9.6 + 9.6 = 147.2 \text{ km}^3 \quad [\text{Eq. 4}]$$

548 and

$$549 \quad V_{imax} = V_{pr} + V_m + V_{intr} + 2V_e = 67 + 67 + 43.2 + 9.6 + 9.6 = 196.4 \text{ km}^3 \quad [\text{Eq. 5}]$$

550 The total bulk PDC volume obtained by (4) and (5) is 147.2 – 196.4 km³ (Table 3). The co-ignimbrite volume
551 (V_{ci}) is estimated using the formula (6) based on the crystal concentration method proposed by Scarpati et al.,
552 2014 (3):

$$553 \quad V_{ci} = \text{Vitric loss} * V_i / (1 - \text{Vitric loss}) = 0.65 * V_i / (1 - 0.65) = 273.4 - 364.7 \text{ km}^3 \quad [\text{Eq. 6}]$$

554 The co-ignimbrite volume, using a vitric loss of 0.65, ranges between 273.4 km³ and 364.7 km³ (107.6 km³ –
555 143.5 km³ DRE). However, V_{ci} could change a lot, according to the value of vitric loss used. From the
556 literature, Walker (1972) proposed for the outcrop of Altavilla (WGI), near Benevento, a vitric loss of 0.55.
557 Using this data, the co-ignimbrite bulk volume decreases and it is substantially lower between 168.2 km³ and
558 240.0 km³. It is necessary great attention to the right value of vitric loss to use, which can significantly influence
559 the total eruptive volume. In this work, we use 0.65, proposed by Scarpati et al. (2014), which is an average of
560 more samples located in several sites all over the CI distribution and from different units (WGI, LYT and
561 CPF). Moreover, it is not quite far from 0.55 previously proposed in literature (Walker, 1972) and the co-
562 ignimbrite volume obtained agrees with the one proposed by Costa et al. (2012) (250 - 300 km³) using the fit
563 of an advection – diffusion tephra dispersion model to thickness data.

564 The total volume of the material erupted during the PDC phase of the CI eruption ranges between 411 km³ and
565 561.1 km³ (163.2 km³ – 225.1 km³ DRE) (Table 3). This estimate is based on the actual preserved deposits of
566 the CI so that all proposed corrections are grounded in a real starting value. Among the previous estimates
567 presented in the literature, the closest to our PDC volume are those proposed by Giaccio (2006) and Pappalardo
568 et al. (2008).

569 The fallout volume considered in this chapter is the minimum and the maximum proposed in literature by
570 Perrotta and Scarpati (2003) and Marti et al. (2016). However, no attempt is made here to evaluate or revise
571 that volume, so we do not prefer any of the previous estimates for the fallout volume and any of them could
572 be used in our total volume estimate. The total volume estimate ranges from 415 km³ to 615.1 km³ (164.9 km³
573 – 247.7 km³ DRE) (Table 3). These values are similar to some previously proposed total volumes (Cornell et
574 al., 1983; Costa et al., 2012; F. G. Fedele et al., 2003; Giaccio, 2006; Pappalardo et al., 2008; Pyle et al., 2006).
575 However, the volume proposed in this work is strictly related to the preserved volume, for the first time clearly
576 constrained by field data. The approach used in this work strongly reduces the errors and uncertainties of the
577 previous calculations.

578 The mass associated with this volume estimate is (7):

$$579 \quad \text{mass}_{min} = 164.9 \text{ km}^3 * 2608 \text{ kg/m}^3 = 4.30 * 10^{14} \text{ kg} \quad [\text{Eq. 7}]$$

580 And (8)

581
$$mass_{max} = 210.7 \text{ km}^3 * 2608 \text{ kg/m}^3 = 6.46 * 10^{14} \text{ kg} \quad [\text{Eq. 8}]$$

582 and the magnitude (M) (9) (Mason et al., 2004):

583
$$M = \log_{10}(mass) - 7 = 7.7 \quad [\text{Eq. 9}]$$

584 This value is consistent with a VEI 7 and a M = 7.7, which makes this eruption the largest Quaternary event
585 from the Campi Flegrei caldera and in Europe. Our new volume estimates should help constrain the modeling
586 of the impact on climate and the environment, including on the history of migrations of humans.

587

588 **7. Conclusions**

589 The CI eruption is the largest eruptive event of the CF caldera and a fundamental chronological marker in all
590 central and eastern Europe. The strong impacts of this eruption on the climate induced a “volcanic winter”
591 with a cooling effect of ~6-9°C in Eastern Europe (Black et al., 2015). The CI eruption influenced the migration
592 of the hominid groups and it had great effects on the Paleolithic societies (Black et al., 2015; Marti et al.,
593 2016). However, the volume of CI, fundamental to the climate impact and simulations, is poorly constrained.

594 Here we present a new method to trace isopachs based on the extrapolation of the paleo-topography that works
595 well in valley-ponded ignimbrites such as the CI. A new isopach map of the extracaldera sub-aerial CI
596 pyroclastic flow deposits yields a volume of $61.5 \text{ km}^3 \pm 5.5 \text{ km}^3$. The greater part of this volume is in the
597 proximal area ($46.4 \pm 1.6 \text{ km}^3$, ~75%) while only around the 25% of the volume is in the distal region after the
598 Apennines Mountain ($15.1 \pm 3.9 \text{ km}^3$).

599 Evidences suggest that the same amount of material should be both on land and offshore (e.g. the radial
600 spreading of the flow). The generated submarine currents could have produced a large amount of
601 volcanoclastic deposits in all the submarine canyons in the Gulf of Naples, as in large part of the Tyrrhenian
602 Sea and possibly had a strong impact on the underwater dynamics of that area. Furthermore, the observation
603 of this volcanoclastic layer can help the correlation and the understanding of sediment cores. Including separate
604 estimates of the marine volume, the volume removed by erosion, the intracaldera volume, and the co-
605 ignimbrite ash volume yields a total volume erupted during the PDC phase of 411.0 km^3 to 561.1 km^3 (163.2
606 $\text{km}^3 - 225.1 \text{ km}^3$ DRE), values in agreement with Giaccio (2006) and Pappalardo et al. (2008).

607 A series of error analyses and corrections were applied to reach a total (including Plinian fallout) final volume
608 estimate: $415.0 \text{ km}^3 - 615.1 \text{ km}^3$ ($164.9 \text{ km}^3 - 247.7 \text{ km}^3$ DRE, in agreement with Cornell et al. (1983), Costa
609 et al. (2012), Fedele et al. (2003), Giaccio (2006), Pappalardo et al. (2008), Pyle et al. (2006)). The volume of
610 material, ash and aerosols is extremely important to understand and model the climate impact of this eruption,
611 which could affect the intensity of solar radiation and consequently cause short-lived climate changes in a
612 critical period for the modern human as the Middle to Upper Paleolithic transition.

613 This volume corresponds to a mass of $4.30 - 6.46 \times 10^{14}$ kg, to a magnitude of 7.7 and to a VEI 7. This was a
614 high impact event with significant effect on the climate and populations of the Paleolithic European region and
615 is a proof that the Campi Flegrei caldera was able to generate a devastating eruption of this dimension.

616

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621 in Data Repository, online at <https://mfr.osf.io/render?url=https%3A%2F%2Fosf.io%2F3a6bz%2Fdownload>.

622

623 **CRedit authorship contribution statement**

624 AS: Conceptualization, Data Curation, Formal analysis, Funding acquisition, Investigation, Methodology,
625 Validation, Visualization, Writing – Original Draft, Writing – Review & Editing. GG: Conceptualization,
626 Funding acquisition, Methodology, Resources, Supervision, Writing – Review & Editing. RI: Resources,
627 Supervision, Writing – Review & Editing. MHO: Funding acquisition, Writing – Review & Editing.

628

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Authors	Volume calculations (km ³)					
	Plinian fallout	Co-plinian ash	PDC	Co-ignimbrite ash	Y-5	Total
Thunell et al., 1979			30-40*		30-40*	60-80*
Cornell et al., 1983					73	>150
Fisher et al., 1993			500			
Civetta et al., 1997	25*		120*			145*
Rosi et al., 1999	15					
Fedele et al., 2003						200*
Perrotta and Scarpati, 2003	4	16		100 (42*)		
Rolandi et al., 2003			180	140		320 (200*)
Giaccio, 2006	10 (3*)		385 (215*)	180 (86*)		575 (300*)
Marianelli et al., 2006	20*		130*			150*
Pyle et al., 2006				72-120 (31-50*)		105-210*
Pappalardo et al., 2008	20*		180*			200*
Costa et al., 2012				250-300 (104-125*)		430-680 (180-280*)
Scarpati et al., 2014			54 (25*)	100 (42*)		207.9 (84.2*)
Marti et al., 2016	54 (22.6*)			153.9 (61.6*)		(84.2*)
Scarpati and Perrotta, 2016	5.33 (0.88*)	14.67 (6.88*)				

1023 **Table 1.** Bulk and DRE (*) volume calculations proposed for the CI by different authors, in approximate
 1024 chronological order. Y-5 refers to those studies that did not identify the co-plinian and co-ignimbrite
 1025 contribution. The methods are described in the text.

1026

Thickness (km)	Area (m ²)	Area (km ²)	Cumulative area (km ²)	Volume (km ³)	Cumulative Volume (km ³)	Volume (%)
0.08	12613584.05	12.61	12.61	0.19	0.19	0.33
0.07	12329142.98	12.33	24.94	0.16	0.35	0.28
0.06	19116655.52	19.12	44.06	0.25	0.60	0.44
0.05	31312007.72	31.31	75.37	1.33	1.92	2.34
0.04	234023868.7	234.02	309.40	2.14	4.07	3.78
0.03	194514229.9	194.51	503.91	5.24	9.31	9.24
0.02	853977772.9	853.98	1357.89	8.58	17.89	15.13
0.01	862025846	862.03	2219.91	9.29	27.18	16.38
0		995.70	3215.61	34.32	61.50	60.52

1027 **Table 2.** The values of thickness (m), area (km²), volume (km³), cumulative volume (km³) and the percentage
 1028 of volume for each isopach.

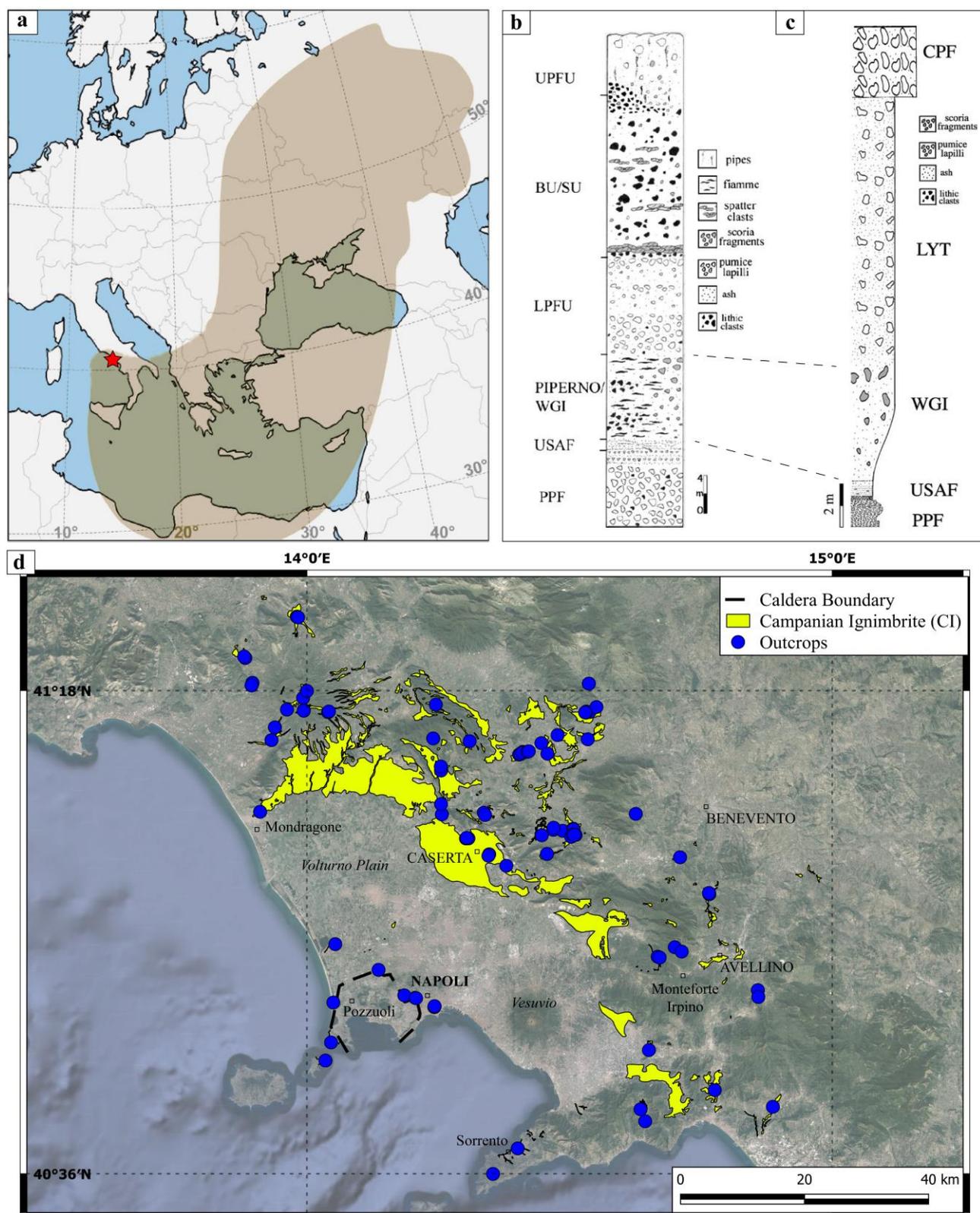
1029

1030

	Bulk Volume (km³)	DRE Volume (km³)
Preserved extra-caldera ignimbrite volume	56 – 67	22.0 – 26.4
Marine volume	56 – 67	22.0 – 26.4
Intracaldera volume	16 – 43.2	7.9 – 21.4
Areal erosion	9.6	3.7
Co-ignimbrite ash volume	273.4 – 364.7	107.6 – 143.5
Total PDC volume	411 – 561.1	163.2 – 225.1
Fallout volume (Marti et al., 2016; Perrotta & Scarpati, 2003)	4 – 54	1.7 – 22.6
Total CI volume	415 – 615.1	164.9 – 247.7

1031 **Table 3.** *The volume of the CI eruption. The various parts of the PDC volume estimate are explained in the*
1032 *text. The fallout volume considered in this work is the maximum and the minimum proposed in literature by*
1033 *Perrotta and Scarpati (2003) and Marti et al. (2016).*

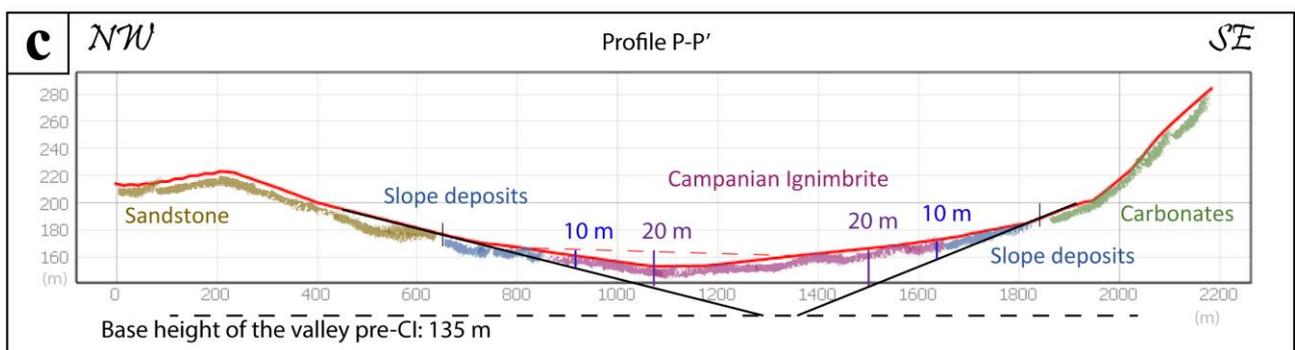
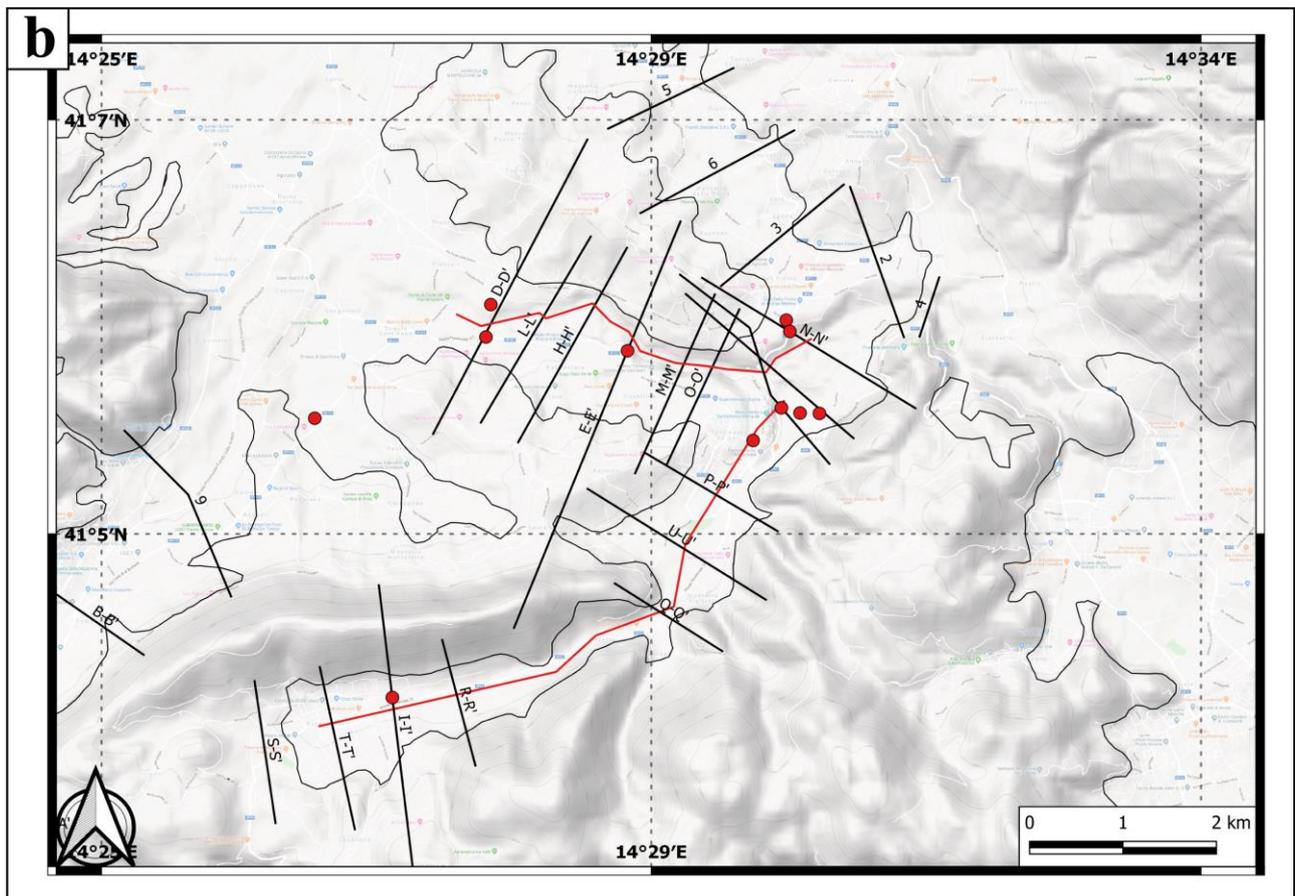
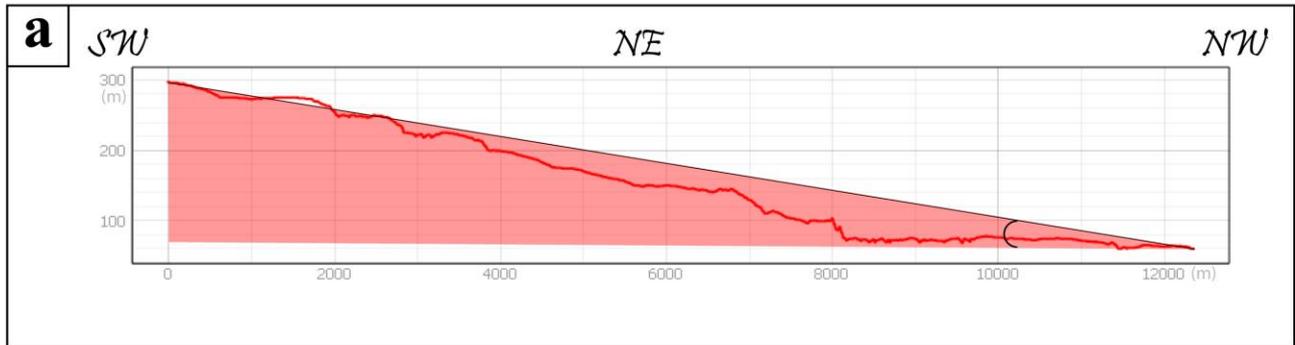
1034



1036

1037 **Figure 1.** The Campanian Ignimbrite distribution. (a) Dispersal area of the CI tephra from the Campi Flegrei
 1038 caldera (red star), modified from Giaccio et al. (2017). Stratigraphic type-sections of CI proximal (b) and
 1039 distal (c) deposits modified from Fedele et al. (2008) and Cappelletti et al. (2003), respectively. (d) The

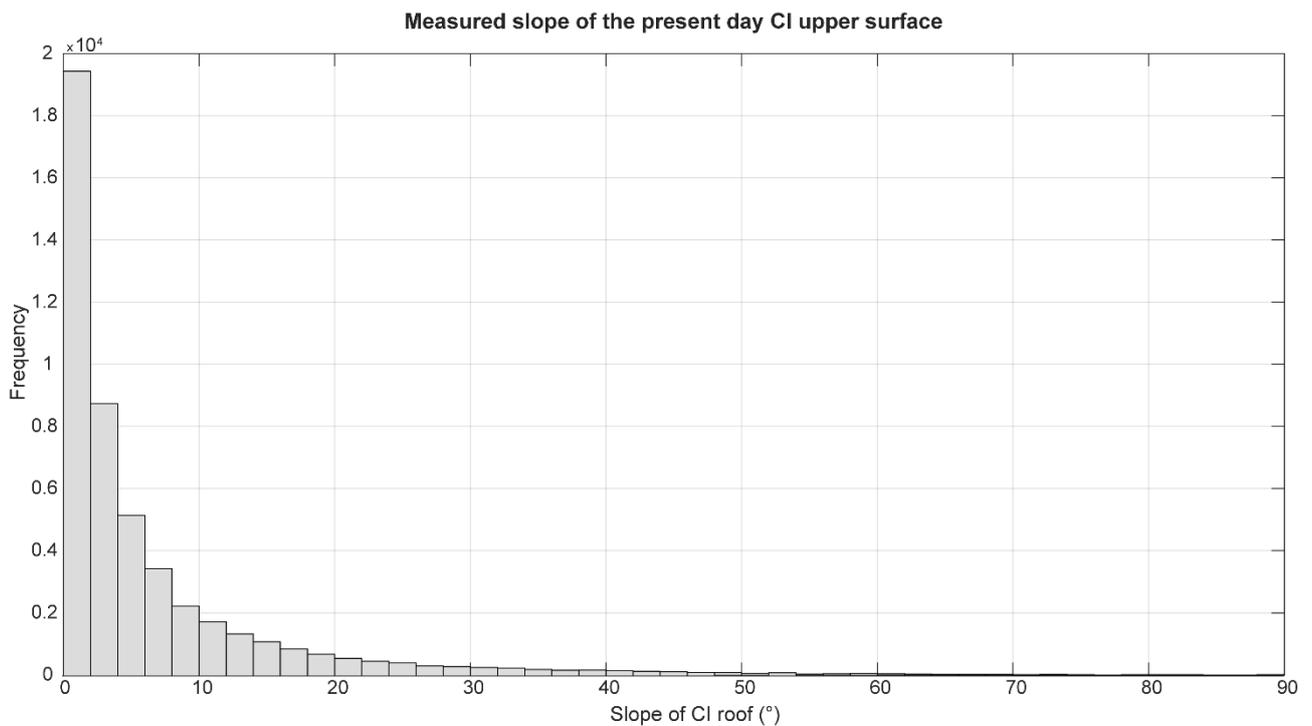
1040 Campanian Ignimbrite distribution in the Campanian region (the base map is from Google Satellite). Blue
 1041 dots indicate the location of the studied outcrops (coordinates are reported in Appendix). The maps were
 1042 generated using the QGIS Open-Source 3.4 (<https://www.qgis.org/it/site/>).



1043

1044 **Figure 2.** The topography reconstruction in the Sant'Agata dei Goti area. (a) The modern valley is used as a
1045 reference for the paleo-slope during the CI eruption. (b) A series of profiles traced to study the paleo-valley;
1046 the red dots are outcrops where the CI is exposed. (c) Reconstruction of the paleo-valley in profile P-P', the
1047 base elevation is constrained to the CI base observed by fieldwork and to the current slope of the valley. The
1048 resulting thickness is always coherent with fieldwork, so where thicknesses are too high, they weren't
1049 considered and the isopachs were traced up to a realistic thickness. The numbers represent the thickness of
1050 the CI in meters.

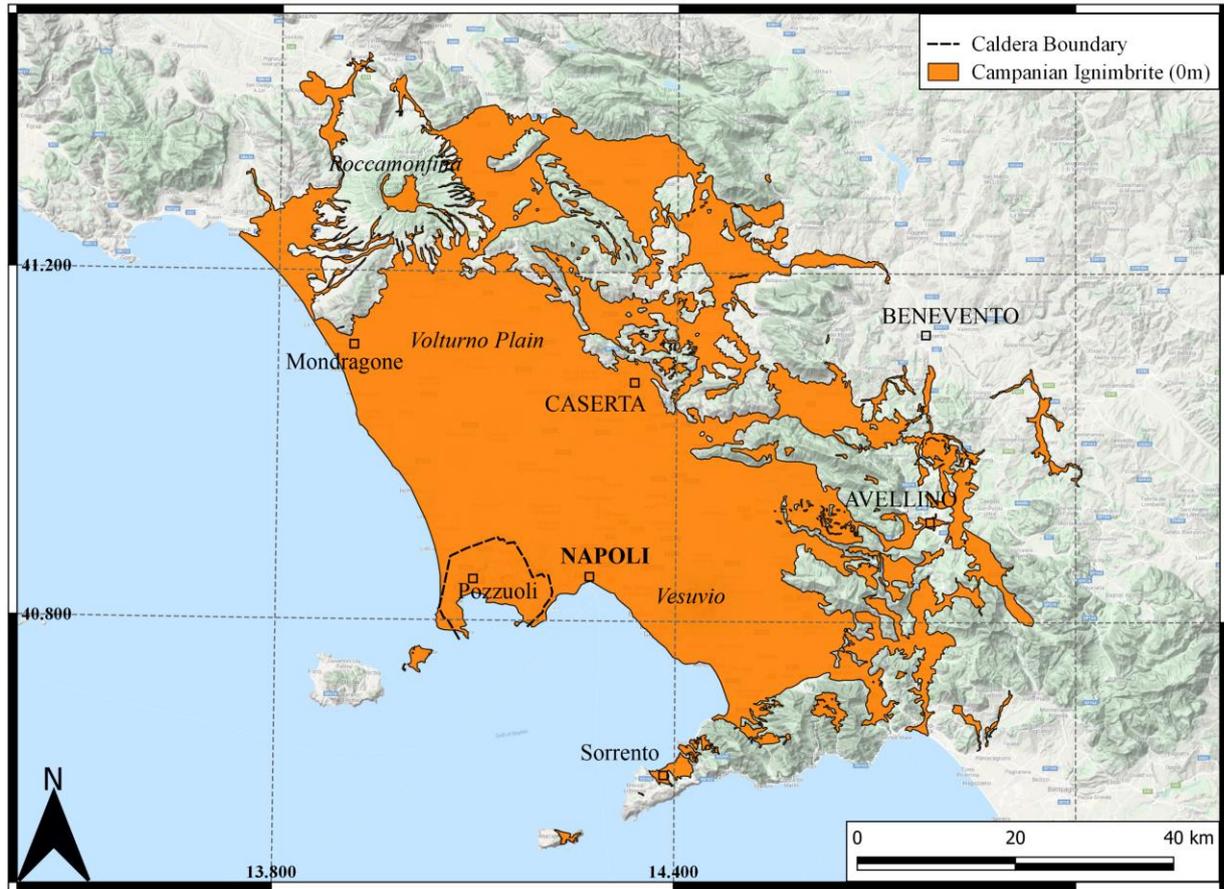
1051



1052

1053 **Figure 3.** Frequency of the slope of the upper surface of the CI. At least 80% of the exposed CI upper surface
1054 slopes less than 10°.

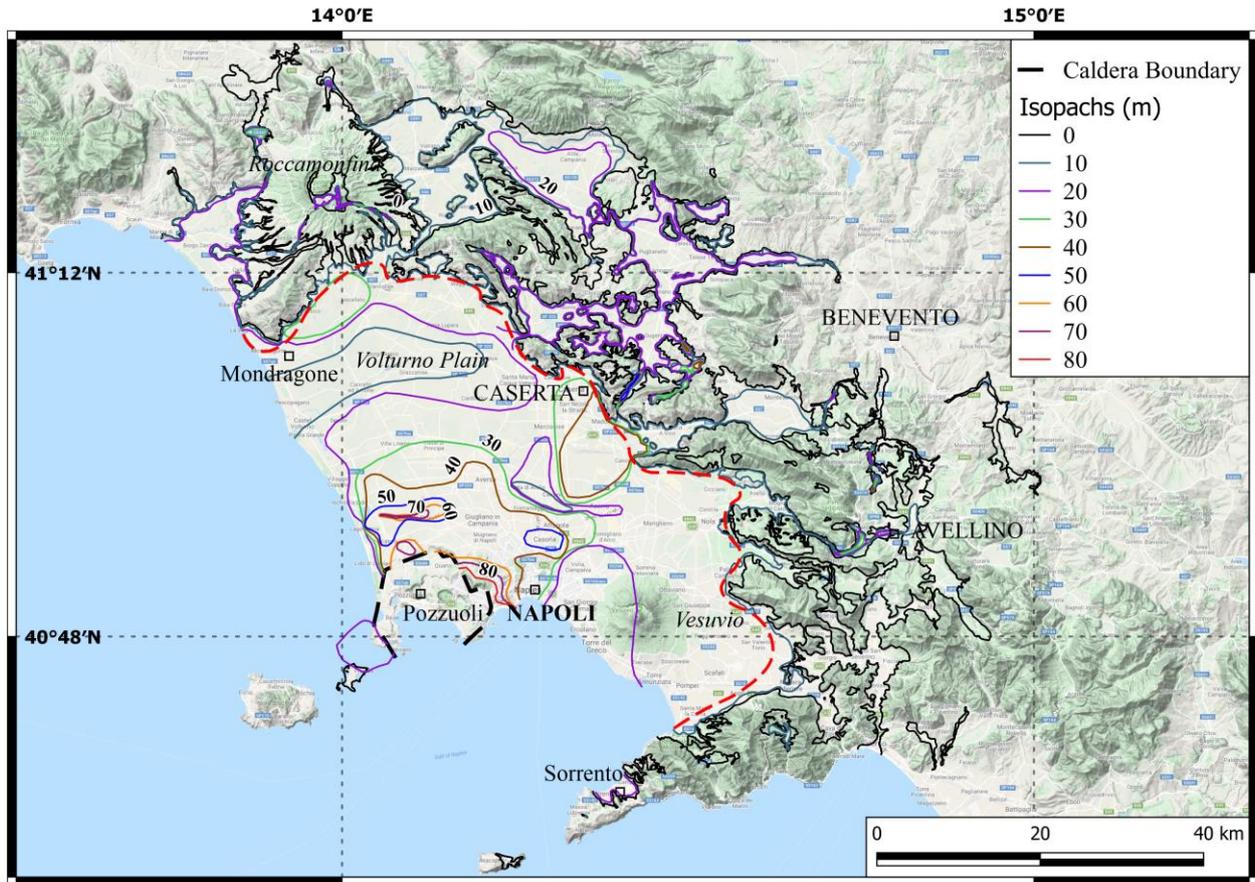
1055



1056

1057 **Figure 4.** The areal extent of the CI, enclosed within the isopach 0 m is shown in orange. The total area
 1058 covered by the preserved deposits of CI is 3216 km², the envelopment with a shape is equal to 7547 km².

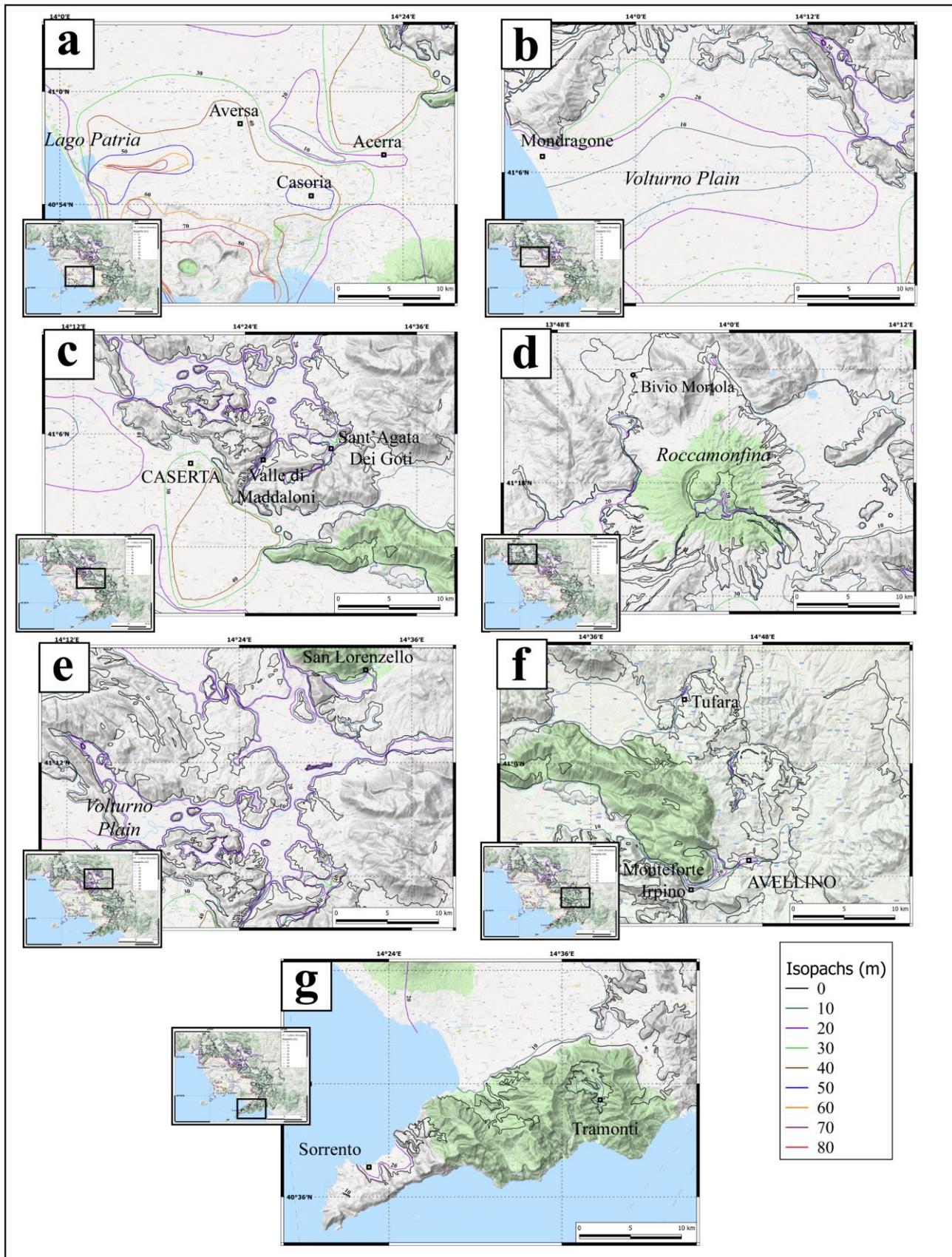
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1061 **Figure 5.** Isopach map of the preserved extra-caldera deposits of the Campanian Ignimbrite. This map refers
 1062 only to the pyroclastic density current deposits; it excludes the Plinian fallout and the co-ignimbrite ash. The
 1063 different colors for each isopach are reported in the map key. The red dashed line divides the proximal and
 1064 the distal area.

1065

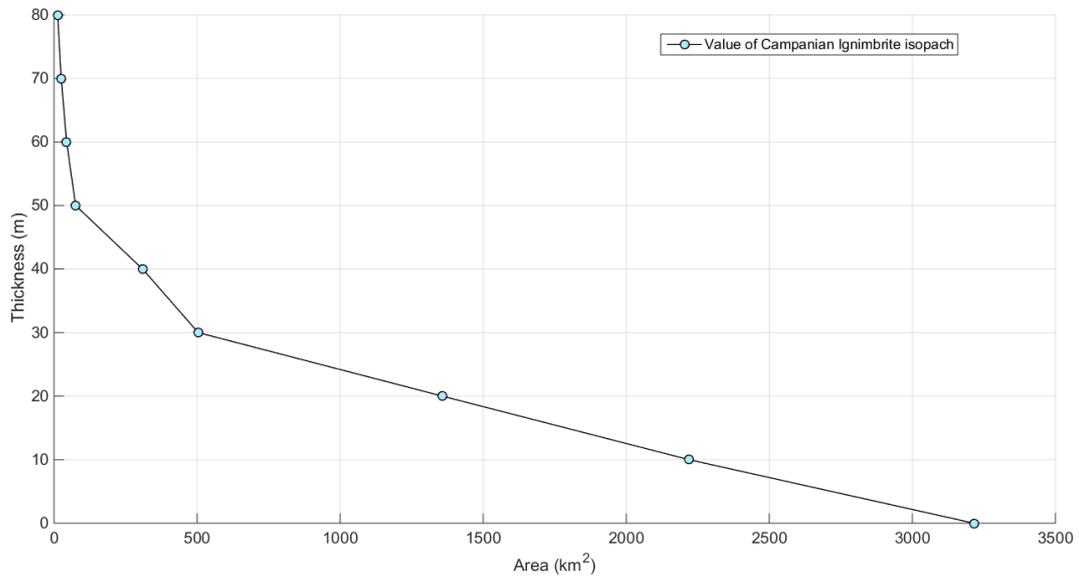


1066

1067 **Figure 6.** Detailed isopach maps of selected areas of the Campanian Ignimbrite (excludes fallout): (a) north
 1068 of the caldera, between Lago Patria and Acerra; (b) northern part of the Campanian Plain; (c) Apennine
 1069 ridges east of the Campi Flegrei caldera and the Valley of Maddaloni; (d) Roccamonfina and Mortola, in the

1070 north of the studied area; (e) Volturno plain and San Lorenzello area, northeast of the caldera; (f) distal area
1071 of Avellino, southeast of the caldera; (g) Sorrento peninsula, in the southern part of the studied area.

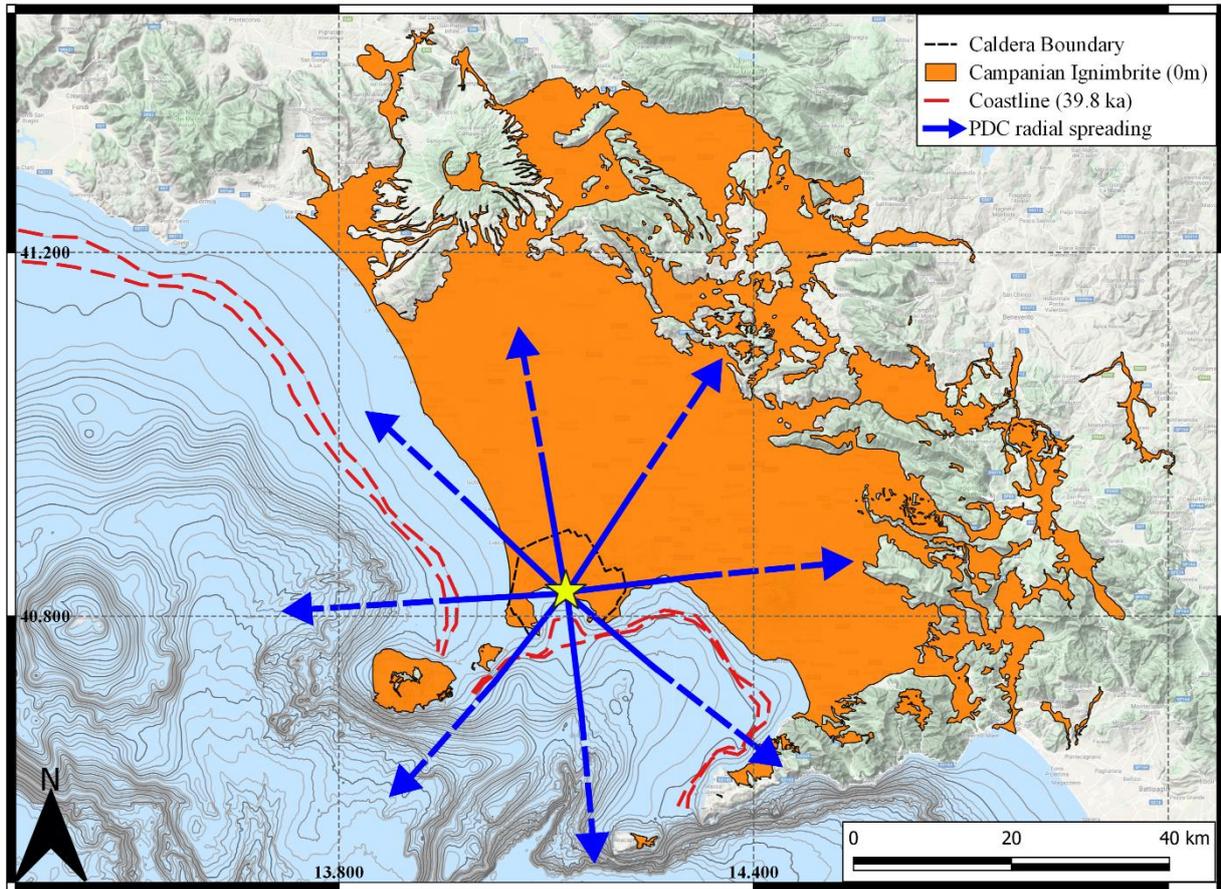
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1074 **Figure 7.** The thickness (m) plotted against the area (km²) of each isopach of the preserved deposits of the CI
1075 PDC. The volume is the subtended area of this plot.

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1077

1078 **Figure 8.** Bathymetry of the submerged area of the Campi Flegrei Caldera. The red line is the 40 ka coastline,
 1079 equivalent to -75 – -87 m of the present one. The blue arrows indicate the possible radial spreading of the
 1080 PDC based on outcrops disposed radially from the center of the Caldera (yellow star) and turbidity currents
 1081 in the Tyrrhenian Sea.

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