

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

2

3 Aurora Silleni^{1#}, Guido Giordano¹, Roberto Isaia², Michael H. Ort³

4 # corresponding author: aurora.silleni@uniroma3.it

5 1- Dipartimento di Scienze, Università di Roma Tre, Largo S. Leonardo Murialdo 1, 00146, Rome, Italy

6 2- Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Via Diocleziano 328, 80124
7 Naples, Italy

8 3- SES, Box 4099, Northern Arizona University, Flagstaff, AZ 86011-4099, USA

9

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

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

31

32 **Plain Language Summary**

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

44

45 **Index Terms**

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

48 **Keywords**

Campanian Ignimbrite; Campi Flegrei; Isopach maps; Ignimbrite volumes; Pyroclastic density currents; Super-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

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

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

2. Volcanological background

The activity in the Campi Flegrei began prior to 80 ka (Pappalardo et al., 1999; Scarpati et al., 2013). The area consists of two nested depressions formed and activated during both the CI and the more recent ~15 ka 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

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

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

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

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

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

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

To summarize, the existing estimates of the total DRE volume of the CI eruption range from 60 to 300 km³ (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 $40 \pm 5\%$ of the volume of tephra within 850 km of the vent is related to the Plinian phase. Furthermore, they
524 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 $147.2 - 196.4 \text{ km}^3$ (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):

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

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):

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

580 And (8)

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

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

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

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

7. Conclusions

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

Here we present a new method to trace isopachs based on the extrapolation of the paleo-topography that works well in valley-ponded ignimbrites such as the CI. A new isopach map of the extracaldera sub-aerial CI 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 proximal area ($46.4 \pm 1.6 \text{ km}^3$, $\sim 75\%$) while only around the 25% of the volume is in the distal region after the Apennines Mountain ($15.1 \pm 3.9 \text{ km}^3$).

Evidences suggest that the same amount of material should be both on land and offshore (e.g. the radial spreading of the flow). The generated submarine currents could have produced a large amount of volcanoclastic deposits in all the submarine canyons in the Gulf of Naples, as in large part of the Tyrrhenian Sea and possibly had a strong impact on the underwater dynamics of that area. Furthermore, the observation of this volcanoclastic layer can help the correlation and the understanding of sediment cores. Including separate estimates of the marine volume, the volume removed by erosion, the intracaldera volume, and the co-ignimbrite ash volume yields a total volume erupted during the PDC phase of 411.0 km^3 to 561.1 km^3 ($163.2 \text{ km}^3 - 225.1 \text{ km}^3$ 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 $4.30 - 6.46 \times 10^{14} \text{ kg}$, 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

617 **Acknowledgments and Data**

618 AS and GG gratefully acknowledge The Grant of Excellence Departments, MIUR-Italy. AS thanks Emanuele
619 Sciarrino and Rose Gallo for their help in the fieldwork. We thank Danilo M. Palladino for discussions. Partial
620 support for some field costs was provided by NSF EAR1761713 to MHO. The data presented here are available
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

629 **References**

630 Acocella, V. (2008). Activating and reactivating pairs of nested collapses during caldera-forming eruptions:
631 Campi Flegrei (Italy). *Geophysical Research Letters*, 35(17), 1–5.
632 <https://doi.org/10.1029/2008GL035078>

- 633 Albert, P. G., Giaccio, B., Isaia, R., Costa, A., Niespolo, E. M., Nomade, S., et al. (2019). Evidence for a
634 large-magnitude eruption from Campi Flegrei caldera (Italy) at 29 ka. *Geology*, 47(7), 595–599.
635 <https://doi.org/10.1130/G45805.1>
- 636 Allen, S. R., & Cas, R. A. F. (2001). Transport of pyroclastic flows across the sea during the explosive,
637 rhyolitic eruption of the Kos Plateau Tuff, Greece. *Bulletin of Volcanology*, 62(6–7), 441–456.
638 <https://doi.org/10.1007/s004450000107>
- 639 Anikovich, M., Sinitsyn, A. A., Hoffecker, J. F., Holliday, V. T., Popov, V. V., Lisitsyn, S. N., et al. (2007).
640 Early Upper Paleolithic in Eastern Europe and Implications for the Dispersal of Modern Humans.
641 *Science*, 315(5809), 223–226. <https://doi.org/10.1126/science.1133376>
- 642 Antonioli, F. (2012). Sea level change in Western-Central Mediterranean since 300 kyr: Comparing global
643 sea level curves with observed data. *Alpine and Mediterranean Quaternary*, 25(1), 15–23.
- 644 Antonioli, F., Bard, E., Potter, E. K., Silenzi, S., & Imbrota, S. (2004). 215-ka history of sea-level
645 oscillations from marine and continental layers in Argentarola Cave speleothems (Italy). *Global and*
646 *Planetary Change*, 43(1–2), 57–78. <https://doi.org/10.1016/j.gloplacha.2004.02.004>
- 647 Barberi, F., Innocenti, F., Lirer, L., Munno, R., Pescatore, T., & Santacroce, R. (1978). The campanian
648 ignimbrite: a major prehistoric eruption in the Neapolitan area (Italy). *Bulletin Volcanologique*, 41(1),
649 10–31. <https://doi.org/10.1007/BF02597680>
- 650 Barsotti, S., Neri, A., & Scire, J. S. (2008). The VOL-CALPUFF model for atmospheric ash dispersal: 1.
651 Approach and physical formulation. *Journal of Geophysical Research: Solid Earth*, 113(3), 1–12.
652 <https://doi.org/10.1029/2006JB004623>
- 653 Bellucci, F. (1994). Nuove conoscenze stratigrafiche sui depositi vulcanici del sottosuolo del settore
654 meridionale della piana campana. *Boll. Soc. Geol. It.*, 113, 395–420.
- 655 Black, B. A., Neely, R. R., & Manga, M. (2015). Campanian Ignimbrite volcanism, climate, and the final
656 decline of the Neanderthals. *Geology*, 43(5), 411–414. <https://doi.org/10.1130/G36514.1>
- 657 Bonadonna, C., & Phillips, J. C. (2003). Sedimentation from strong volcanic plumes. *Journal of Geophysical*

- 658 *Research: Solid Earth*, 108(B7), 1–28. <https://doi.org/10.1029/2002jb002034>
- 659 Bonadonna, C., Ernst, G. G. J., & Sparks, R. S. J. (1998). Thickness variations and volume estimates of
660 tephra fall deposits: the importance of particle Reynolds number. *Journal of Volcanology and*
661 *Geothermal Research*, 81(3–4), 173–187. [https://doi.org/10.1016/S0377-0273\(98\)00007-9](https://doi.org/10.1016/S0377-0273(98)00007-9)
- 662 Bonadonna, C., Connor, C. B., Houghton, B. F., Connor, L., Byrne, M., Laing, A., & Hincks, T. K. (2005).
663 Probabilistic modeling of tephra dispersal: Hazard assessment of a multiphase rhyolitic eruption at
664 Tarawera, New Zealand. *Journal of Geophysical Research: Solid Earth*, 110(3), 1–21.
665 <https://doi.org/10.1029/2003JB002896>
- 666 Bluszcz, A., Hercman, H., Pazdur, A., Pazdur, M. (1992). Radiometric dating. In *Temnata Cave.*
667 *Excavations in Karlukovo Karst Area, Bulgaria*, vol. 1.1, ed. By J.K. Kozłowski, H. Laville and B.
668 Ginter, pp. 223-240. Cracow: Jagellonian University Press.
- 669 Capocci, E. (1835). Nuove ricerche sul noto fenomeno delle colonne perforate dale Foladi nel tempio di
670 Serapide in Pozzuoli.
- 671 Cappelletti, P., Cerri, G., Colella, A., de’Gennaro, M., Langella, A., Perrotta, A., & Scarpati, C. (2003). Post-
672 eruptive processes in the Campanian Ignimbrite. *Mineralogy and Petrology*, 79(1–2), 79–97.
673 <https://doi.org/10.1007/s00710-003-0003-7>
- 674 Carey, S., Sigurdsson, H., Mandeville, C., & Bronto, S. (1996). Pyroclastic flows and surges over water: an
675 example from the 1883 Krakatau eruption. *Bulletin of Volcanology*, 57(7), 493–511.
676 <https://doi.org/10.1007/BF00304435>
- 677 Cashman, K. V., & Giordano, G. (2014). Calderas and magma reservoirs. *Journal of Volcanology and*
678 *Geothermal Research*, 288, 28–45. <https://doi.org/10.1016/j.jvolgeores.2014.09.007>
- 679 Castagnoli, G. C., Albrecht, A., Beer, J., Shen, C., Callegari, E., Taricco, C., et al. (1995). Evidence for
680 enhanced ¹⁰Be deposition in Mediterranean sediments 35 Kyr BP. *Geophysical Research Letters*,
681 22(6), 707–710.
- 682 Civetta, L., Orsi, G., Pappalardo, L., Fisher, R. V., Heiken, G., & Ort, M. H. (1997). Geochemical zoning,

683 mingling, eruptive dynamics and depositional processes - the Campanian Ignimbrite, Campi Flegrei
684 caldera, Italy. *Journal of Volcanology and Geothermal Research*, 75, 183–219.

685 Cornell, W., Carey, S., & Sigurdsson, H. (1983). Computer simulation of transport and deposition of the
686 campanian Y-5 ash. *Journal of Volcanology and Geothermal Research*, 17(1–4), 89–109.
687 [https://doi.org/10.1016/0377-0273\(83\)90063-X](https://doi.org/10.1016/0377-0273(83)90063-X)

688 Costa, A., Macedonio, G., & Folch, A. (2006). A three-dimensional Eulerian model for transport and
689 deposition of volcanic ashes. *Earth and Planetary Science Letters*, 241(3–4), 634–647.
690 <https://doi.org/10.1016/j.epsl.2005.11.019>

691 Costa, A., Folch, A., Macedonio, G., Giaccio, B., Isaia, R., & Smith, V. C. (2012). Quantifying volcanic ash
692 dispersal and impact of the Campanian Ignimbrite super-eruption. *Geophysical Research Letters*,
693 39(10), 3–7. <https://doi.org/10.1029/2012GL051605>

694 Costa, A., Suzuki, Y. J., & Koyaguchi, T. (2018). Understanding the plume dynamics of explosive super-
695 eruptions. *Nature Communications*, 9(1). <https://doi.org/10.1038/s41467-018-02901-0>

696 De Natale, G., Troise, C., Mark, D., Mormone, A., Piochi, M., Di Vito, M. A., et al. (2016). The Campi
697 Flegrei Deep Drilling Project (CFDDP): New insight on caldera structure, evolution and hazard
698 implications for the Naples area (Southern Italy). *Geochemistry Geophysics Geosystems*, 17, 2825–
699 2834. <https://doi.org/10.1002/2016GC006406>

700 De Vivo, B., Rolandi, G., Gans, P. B., Calvert, A., Bohrsen, W. A., Spera, F. J., & Belkin, H. E. (2001). New
701 constraints on the pyroclastic eruptive history of the Campanian volcanic Plain (Italy). *Mineralogy and*
702 *Petrology*, 73(1–3), 47–65. <https://doi.org/10.1007/s007100170010>

703 Di Vito, M. A., Isaia, R., Orsi, G., Southon, J., De Vita, S., D’Antonio, M., et al. (1999). Volcanism and
704 deformation since 12,000 years at the Campi Flegrei caldera (Italy). *Journal of Volcanology and*
705 *Geothermal Research*, 91(2–4), 221–246. [https://doi.org/10.1016/S0377-0273\(99\)00037-2](https://doi.org/10.1016/S0377-0273(99)00037-2)

706 D’Oriano, C., Poggianti, E., Bertagnini, A., Cioni, R., Landi, P., Polacci, M., & Rosi, M. (2005). Changes in
707 eruptive style during the A.D. 1538 Monte Nuovo eruption (Phlegrean Fields, Italy): The role of syn-
708 eruptive crystallization. *Bulletin of Volcanology*, 67(7), 601–621. <https://doi.org/10.1007/s00445-004->

710 Dufek, J., & Bergantz, G. W. (2007). Dynamics and deposits generated by the Kos Plateau Tuff eruption:
711 Controls of basal particle loss on pyroclastic flow transport. *Geochemistry, Geophysics, Geosystems*,
712 8(12). <https://doi.org/10.1029/2007GC001741>

713 Dufek, J., Manga, M., & Staedter, M. (2007). Littoral blasts: Pumice-water heat transfer and the conditions
714 for steam explosions when pyroclastic flows enter the ocean. *Journal of Geophysical Research: Solid*
715 *Earth*, 112(11), 1–16. <https://doi.org/10.1029/2006JB004910>

716 Engwell, S., Sparks, R. S. J., & Carey, S. (2014). Physical characteristics of tephra layers in the deep sea
717 realm: the Campanian Ignimbrite eruption. *Geological Society, London, Special Publications*, 398(1),
718 47–64. <https://doi.org/10.1144/SP398.7>

719 Fedele, F. G., Giaccio, B., Isaia, R., & Orsi, G. (2002). Ecosystem Impact of the Campanian Ignimbrite
720 Eruption in Late Pleistocene Europe. *Quaternary Research*, 57(3), 420–424.
721 <https://doi.org/10.1006/qres.2002.2331>

722 Fedele, F. G., Giaccio, B., Isaia, R., & Orsi, G. (2003). The Campanian ignimbrite eruption, Heinrich event
723 4, and Palaeolithic change in Europe: a high-resolution investigation. *Geophysical Monograph*, 301–
724 325. <https://doi.org/10.1029/139GM20>

725 Fedele, F. G., Giaccio, B., Isaia, R., Orsi, G., Carroll, M. R., & Scaillet, B. (2007). The Campanian
726 Ignimbrite Factor: Towards a Reappraisal of the Middle to Upper Palaeolithic “Transition.” *Living*
727 *Under The Shadow. Cultural Impacts of Volcanic Eruptions*, 19–41.

728 Fedele, F. G., Giaccio, B., & Hajdas, I. (2008). Timescales and cultural process at 40,000 BP in the light of
729 the Campanian Ignimbrite eruption, Western Eurasia. *Journal of Human Evolution*, 55(5), 834–857.
730 <https://doi.org/10.1016/j.jhevol.2008.08.012>

731 Fedele, L., Scarpato, C., Lanphere, M., Melluso, L., Morra, V., Perrotta, A., & Ricci, G. (2008). The Breccia
732 Museo formation, Campi Flegrei, southern Italy: Geochronology, chemostratigraphy and relationship
733 with the Campanian Ignimbrite eruption. *Bulletin of Volcanology*, 70(10), 1189–1219.
734 <https://doi.org/10.1007/s00445-008-0197-y>

735 Fedele, L., Scarpati, C., Sparice, D., Perrotta, A., & Laiena, F. (2016). A chemostratigraphic study of the
736 Campanian Ignimbrite eruption (Campi Flegrei, Italy): Insights on magma chamber withdrawal and
737 deposit accumulation as revealed by compositionally zoned stratigraphic and facies framework. *Journal*
738 *of Volcanology and Geothermal Research*, 324, 105–117.
739 <https://doi.org/10.1016/j.jvolgeores.2016.05.019>

740 Fisher, R. V., Orsi, G., Ort, M. H., & Heiken, G. (1993). Mobility of a large-volume pyroclastic flow -
741 emplacement of the Campanian ignimbrite, Italy. *Journal of Volcanology and Geothermal Research*,
742 56(3), 205–220. [https://doi.org/10.1016/0377-0273\(93\)90017-L](https://doi.org/10.1016/0377-0273(93)90017-L)

743 Folch, A. (2012). A review of tephra transport and dispersal models: Evolution, current status, and future
744 perspectives. *Journal of Volcanology and Geothermal Research*, 235–236, 96–115.
745 <https://doi.org/10.1016/j.jvolgeores.2012.05.020>

746 Folch, A., Costa, A., Durant, A., & Macedonio, G. (2010). A model for wet aggregation of ash particles in
747 volcanic plumes and clouds: 2. Model application. *Journal of Geophysical Research: Solid Earth*,
748 115(9), 1–16. <https://doi.org/10.1029/2009JB007176>

749 Giaccio, B. (2006). *L'eruzione dell'Ignimbrite Campana (c. 40 ka BP), oscillazioni climatiche sub-orbitali e*
750 *i cambiamenti bioculturali dell'OIS 3 europeo*. Università degli Studi di Napoli "Federico II."

751 Giaccio, B., Hajdas, I., Peresani, M., Fedele, F. G., & Isaia, R. (2006). The Campanian Ignimbrite tephra and
752 its relevance for the timing of the middle to upper paleolithic shift. In *When Neanderthals and modern*
753 *humans met* (pp. 343–375).

754 Giaccio, B., Isaia, R., Fedele, F. G., Di Canzio, E., Hoffecker, J. F., Ronchitelli, A., et al. (2008). The
755 Campanian Ignimbrite and Codola tephra layers: Two temporal/stratigraphic markers for the Early
756 Upper Palaeolithic in southern Italy and eastern Europe. *Journal of Volcanology and Geothermal*
757 *Research*, 177(1), 208–226. <https://doi.org/10.1016/j.jvolgeores.2007.10.007>

758 Giaccio, B., Hajdas, I., Isaia, R., Deino, A. L., & Nomade, S. (2017). dating of the Campanian Ignimbrite (
759 Y-5) reconciles the time-scales of climatic-cultural processes at 40 ka. *Nature Publishing Group*,
760 (January), 1–10. <https://doi.org/10.1038/srep45940>

761 Hajdas, I., Taricco, C., Bonani, G., Beer, J., Bernasconi, S. M., & Wacker, L. (2011). Anomalous
 762 radiocarbon ages found in Campanian Ignimbrite deposit of the Mediterranean deep-sea core CT85-5.
 763 *Radiocarbon*, 53(4), 575–583.

764 Isaia, R., Marianelli, P., & Sbrana, A. (2009). Caldera unrest prior to intense volcanism in Campi Flegrei
 765 (Italy) at 4.0 ka B.P.: Implications for caldera dynamics and future eruptive scenarios. *Geophysical*
 766 *Research Letters*, 36(21), 1–6. <https://doi.org/10.1029/2009GL040513>

767 ISPRA (2009). Geological Map n. 432 “Benevento”; scale 1:50,000. *National Geological Survey of Italy*,
 768 Università degli studi di Urbino, Istituto di Geologia Applicata, Urbino, Italy.

769 ISPRA (2010). Geological Map n. 431 “Caserta Est”; scale 1:50,000. *National Geological Survey of Italy*,
 770 Regione Campania, Settore Difesa Suolo, Napoli, Italy.

771 ISPRA (2011a). Geological Map n. 465 “Isola di Procida”; scale 1:50,000. *National Geological Survey of*
 772 *Italy*, Regione Campania, Settore Difesa Suolo, Napoli, Italy.

773 ISPRA (2011b). Geological Map n. 448 “Ercolano”; scale 1:50,000. *National Geological Survey of Italy*,
 774 CNR Consiglio Nazionale delle Ricerche, Italy.

775 ISPRA (2011c). Geological Map n. 467 “Salerno”; scale 1:50,000. *National Geological Survey of Italy*,
 776 (<http://www.isprambiente.gov.it/MEDIA/carg/campania.html>).

777 ISPRA (2011d). Geological Map n. 446-447 “Napoli”; scale 1:50,000. *National Geological Survey of Italy*,
 778 Regione Campania - Settore Difesa Suolo, Napoli, Italy.

779 ISPRA (2014°). Geological Map n. 450 “S. Angelo dei Lombardi”; scale 1:50,000. *National Geological*
 780 *Survey of Italy*, CNR Consiglio Nazionale delle Ricerche, Italy.

781 ISPRA (2014b). Geological Map n. 466-485 “Sorrento-Termini”; scale 1:50,000. *National Geological*
 782 *Survey of Italy*, CNR Consiglio Nazionale delle Ricerche, Italy.

783 ISPRA (2016). Geological Map n. 449 “Avellino”; scale 1:50,000. *National Geological Survey of Italy*,
 784 Regione Campania, Italy.

785 ISPRA (2018). Geological Map n. 464 “Isola d’Ischia”; scale 1:25,000. *National Geological Survey of Italy*,

786 Regione Campania, Settore Difesa Suolo, Napoli, Italy.

787 Keller, J., Ryan, W. B. F., Ninkovich, D., & Altherr, R. (1978). Explosive volcanic activity in the
788 Mediterranean over the past 200,000 yr as recorded in deep-sea sediments. *Bulletin of the Geological*
789 *Society of America*, 89(4), 591–604. [https://doi.org/10.1130/0016-](https://doi.org/10.1130/0016-7606(1978)89<591:EVAITM>2.0.CO;2)
790 [7606\(1978\)89<591:EVAITM>2.0.CO;2](https://doi.org/10.1130/0016-7606(1978)89<591:EVAITM>2.0.CO;2)

791 Kozlowski, J. K. (1998). The Middle and the Early Upper Paleolithic around the black sea. In *Neandertals*
792 *and Modern Humans in Western Asia* (pp. 461–482). New York: Plenum Press.

793 Lambeck, K., & Bard, E. (2000). Sea-level change along the French Mediterranean coast for the past 30000
794 years. *Earth and Planetary Science Letters*, 175(3–4), 203–222.

795 Langella, A., Bish, D. L., Calcaterra, D., & Cappelletti, P. (2013). L’Ignimbrite Campana (IC). In L. Editore
796 (Ed.), *Le pietre storiche della Campania dall’oblio alla riscoperta* (pp. 155–177).

797 Lowe, J., Barton, N., Blockley, S., Ramsey, C. B., Cullen, V. L., Davies, W., et al. (2012). Volcanic ash
798 layers illuminate the resilience of Neanderthals and early modern humans to natural hazards.
799 *Proceedings of the National Academy of Sciences*, 109(34), 13532–13537.
800 <https://doi.org/10.1073/pnas.1204579109>

801 Marianelli, P., Sbrana, A., & Proto, M. (2006). Magma chamber of the Campi Flegrei supervolcano at the
802 time of eruption of the Campanian Ignimbrite. *Geology*, 34(11), 937–940.
803 <https://doi.org/10.1130/G22807A.1>

804 Marti, A., Folch, A., Costa, A., & Engwell, S. (2016). Reconstructing the plinian and co-ignimbrite sources
805 of large volcanic eruptions: A novel approach for the Campanian Ignimbrite. *Scientific Reports*, 6(1),
806 21220. <https://doi.org/10.1038/srep21220>

807 Mason, B. G., Pyle, D. M., & Oppenheimer, C. (2004). The size and frequency of the largest explosive
808 eruptions on Earth. *Bulletin of Volcanology*, 66(8), 735–748. [https://doi.org/10.1007/s00445-004-0355-](https://doi.org/10.1007/s00445-004-0355-9)
809 [9](https://doi.org/10.1007/s00445-004-0355-9)

810 McCoy, F.W., & Cornell, W. (1990). Volcaniclastic sediments in the Tyrrhenian basin. In K.A. Kastens and

811 J. Mascle et al. (eds.) “*Proceedings of the ODP*”, 291-305. Scientific Results 107.

812 Melekestsev, I.V., Kirianov, V.Y., & Praslov, N.D. (1984). Catastrophic eruption in the Phlegrean Fields
813 region (Italy) - possible source for a volcanic ash in late Pleistocene sediments of the European part of
814 the USSR. *Vulcanologija i Seismologija* 3, 35-44.

815 Melluso, L., Morra, V., Perrotta, A., Scarpati, C., & Adabbo, M. (1995). The eruption of the Breccia Museo
816 (Campi Flegrei, Italy): Fractional crystallization processes in a shallow, zoned magma chamber and
817 implications for the eruptive dynamics. *Journal of Volcanology and Geothermal Research*, 68(4), 325–
818 339. [https://doi.org/10.1016/0377-0273\(95\)00020-5](https://doi.org/10.1016/0377-0273(95)00020-5)

819 Milia, A., & Torrente, M. M. (2007). The influence of paleogeographic setting and crustal subsidence on the
820 architecture of ignimbrites in the Bay of Naples (Italy). *Earth and Planetary Science Letters*, 263, 192–
821 206. <https://doi.org/10.1016/j.epsl.2007.08.004>

822 Mormone, A., Troise, C., Piochi, M., Balassone, G., Joachimski, M., & De Natale, G. (2015). Mineralogical,
823 geochemical and isotopic features of tuffs from the CFDDP drill hole: Hydrothermal activity in the
824 eastern side of the Campi Flegrei volcano (southern Italy). *Journal of Volcanology and Geothermal*
825 *Research*, 290, 39–52. <https://doi.org/10.1016/j.jvolgeores.2014.12.003>

826 Narcisi, B. (1996). Tephrochronology of a late quaternary lacustrine record from the Monticchio maar
827 (Vulture volcano, southern Italy). *Quaternary Science Reviews*, 15(2–3), 155–165.
828 [https://doi.org/10.1016/0277-3791\(95\)00045-3](https://doi.org/10.1016/0277-3791(95)00045-3)

829 Narcisi, B., & Vezzoli, L. (1999). Quaternary stratigraphy of distal tephra layers in the Mediterranean - An
830 overview. *Global and Planetary Change*, 21(1–3), 31–50. [https://doi.org/10.1016/S0921-](https://doi.org/10.1016/S0921-8181(99)00006-5)
831 [8181\(99\)00006-5](https://doi.org/10.1016/S0921-8181(99)00006-5)

832 Orsi, G., De Vita, S., & Di Vito, M. A. (1996). The restless, resurgent Campi Flegrei nested caldera (Italy):
833 constraints on its evolution and configuration. *Journal of Volcanology and Geothermal Research*, 74,
834 179–214.

835 Ort, M. H., Orsi, G., Pappalardo, L., & Fisher, R. V. (2003). Anisotropy of magnetic susceptibility studies of
836 depositional processes in the Campanian Ignimbrite , Italy. *Bulletin of Volcanology*, 65, 55–72.

837 <https://doi.org/10.1007/s00445-002-0241-2>

838 Ortolani, F., & Aprile, F. (1985). Principali caratteristiche stratigrafiche e strutturali dei depositi superficiali
839 della piana campana. *Boll. Soc. Geol. It.*, 104, 195–206.

840 Pappalardo, L., Civetta, L., D’Antonio, M., Deino, A. L., Di Vito, M. A., Orsi, G., et al. (1999). Chemical
841 and Sr-isotopical evolution of the Phlegraean magmatic system before the Campanian Ignimbrite and
842 the Neapolitan Yellow Tuff eruptions. *Journal of Volcanology and Geothermal Research*, 91(2–4),
843 141–166. [https://doi.org/10.1016/S0377-0273\(99\)00033-5](https://doi.org/10.1016/S0377-0273(99)00033-5)

844 Pappalardo, L., Ottolini, L., & Mastrolorenzo, G. (2008). The Campanian Ignimbrite (southern Italy)
845 geochemical zoning: Insight on the generation of a super-eruption from catastrophic differentiation and
846 fast withdrawal. *Contributions to Mineralogy and Petrology*, 156(1), 1–26.
847 <https://doi.org/10.1007/s00410-007-0270-0>

848 Parfitt, L., & Wilson, L. (2008). *Fundamentals of Physical Volcanology*. Blackwell, Malden, USA (256 pp.).

849 Paterne, M. (1992). Additional remarks on tephra layer from Temnata Cave, in *Temnata Cave. Excavations*
850 *in Karlukovo Karst area, Bulgaria*, edited by J.K. Kozłowski, H. Laville and B. Ginter, pp. 99–100,
851 Jagellonian University Press, Cracow.

852 Paterne, M., Guichard, F., Labeyrie, J., Gillot, P. Y., & Duplessy, J. C. (1986). Tyrrhenian Sea
853 tephrochronology of the oxygen isotope record for the past 60,000 years. *Marine Geology*, 72(3–4),
854 259–285. [https://doi.org/10.1016/0025-3227\(86\)90123-4](https://doi.org/10.1016/0025-3227(86)90123-4)

855 Paterne, M., Kallel, N., Labeyrie, L., Vautravers, M., Duplessy, J. C., Rossignol-Strick, M., et al. (1999).
856 Hydrological relationship between the North Atlantic Ocean and the Mediterranean Sea during the past
857 15 - 75 kyr. *Paleoceanography*, 14(5), 626–638. <https://doi.org/10.1029/1998PA900022>

858 Perrotta, A., & Scarpati, C. (1994). The dynamics of the Breccia Museo eruption (Campi Flegrei, Italy) and
859 the significance of spatter clasts associated with lithic breccias. *Journal of Volcanology and*
860 *Geothermal Research*, 59(4), 335–355. [https://doi.org/10.1016/0377-0273\(94\)90086-8](https://doi.org/10.1016/0377-0273(94)90086-8)

861 Perrotta, A., & Scarpati, C. (2003). Volume partition between the plinian and co-ignimbrite air fall deposits

862 of the Campanian Ignimbrite eruption. *Mineralogy and Petrology*, 79(1–2), 67–78.
863 <https://doi.org/10.1007/s00710-003-0002-8>

864 Perrotta, A., Scarpati, C., Luongo, G., & Morra, V. (2006). Chapter 5 The Campi Flegrei caldera boundary in
865 the city of Naples. *Developments in Volcanology*, 9(C), 85–96. [https://doi.org/10.1016/S1871-](https://doi.org/10.1016/S1871-644X(06)80019-7)
866 [644X\(06\)80019-7](https://doi.org/10.1016/S1871-644X(06)80019-7)

867 Perrotta, A., Scarpati, C., Luongo, G., & Morra, V. (2010). Stratigraphy and volcanological evolution of the
868 southwestern sector of Campi Flegrei and Procida Island , Italy. *The Geological Society of America*
869 *Special Paper*, 80301(303), 171–191. [https://doi.org/10.1130/2010.2464\(09\)](https://doi.org/10.1130/2010.2464(09)).

870 Piochi, M., Mastrolorenzo, G., & Pappalardo, L. (2005). Magma ascent and eruptive processes from textural
871 and compositional features of Monte Nuovo pyroclastic products, Campi Flegrei, Italy. *Bulletin of*
872 *Volcanology*, 67(7), 663–678. <https://doi.org/10.1007/s00445-005-0410-1>

873 Pyle, D.M. (1990). New volume estimates for the Minoan eruption of Santorini. In: Hardy, D.A., Keller, J.,
874 Galanopoulos, V., Flemming, N.C., Druitt, T.H. (Eds.), *Thera and the Aegean World III*, The Thera
875 Foundation, London, vol. 2, pp. 113–121

876 Pyle, D. M. (1989). The thickness, volume and grainsize of tephra fall deposits. *Bulletin of Volcanology*, 51,
877 1–15.

878 Pyle, D. M., Ricketts, G. D., Margari, V., van Andel, T. H., Sinitsyn, A. A., Praslov, N. D., & Lisitsyn, S. N.
879 (2006). Wide dispersal and deposition of distal tephra during the Pleistocene “Campanian
880 Ignimbrite/Y5” eruption, Italy. *Quaternary Science Reviews*, 25(21–22), 2713–2728.
881 <https://doi.org/10.1016/j.quascirev.2006.06.008>

882 Rampino, M. R., & Self, S. (1992). Volcanic winter and accelerated glaciation following the Toba super-
883 eruption. *Nature*, 359, 50–52.

884 Rolandi, G., Bellucci, F., Heizler, M. T., Belkin, H. E., & De Vivo, B. (2003). Tectonic controls on the
885 genesis of ignimbrites from the Campanian Volcanic Zone, southern Italy. *Mineralogy and Petrology*,
886 79(1–2), 3–31. <https://doi.org/10.1007/s00710-003-0014-4>

- 887 Rosi, M., Sbrana, A. (1987). Phlegrean Fields. CNR, *Quaderni de La ‘Ricerca Scientifica’* 114, 1–175.
- 888 Rosi, M., Sbrana, A., & Principe, C. (1983). The phlegraean fields: Structural evolution, volcanic history and
889 eruptive mechanisms. *Journal of Volcanology and Geothermal Research*, 17(1–4), 273–288.
890 [https://doi.org/10.1016/0377-0273\(83\)90072-0](https://doi.org/10.1016/0377-0273(83)90072-0)
- 891 Rosi, M., Sbrana, A., & Vezzoli, L. (1988). Correlazioni tefrostratigrafiche di alcuni livelli di Ischia, Procida
892 e Campi Flegrei. *Memorie Della Società Geologica Italiana*, 41, 1015–1027.
- 893 Rosi, M., Vezzoli, L., Aleotti, P., & Censi, M. (1996). Interaction between caldera collapse and eruptive
894 dynamics during the Campanian Ignimbrite eruption, Phlegraean Fields, Italy. *Bulletin of Volcanology*,
895 57(7), 541–554. <https://doi.org/10.1007/BF00304438>
- 896 Rosi, M., Vezzoli, L., Castelmennano, A., & Grieco, G. (1999). Plinian pumice fall deposit of the Campanian
897 Ignimbrite eruption (Phlegraean Fields, Italy). *Journal of Volcanology and Geothermal Research*,
898 91(2–4), 179–198. [https://doi.org/10.1016/S0377-0273\(99\)00035-9](https://doi.org/10.1016/S0377-0273(99)00035-9)
- 899 Ruberti, D., Vigliotti, M., Rolandi, R., & Lascio, M. Di. (2020). Effect of paleomorphology on facies
900 distribution of the Campania Ignimbrite in the northern Campania Plain, southern Italy. In *Vesuvius,*
901 *Campi Flegrei, and Campanian Volcanism* (pp. 207–229). Elsevier Inc. [https://doi.org/10.1016/B978-](https://doi.org/10.1016/B978-0-12-816454-9.00009-2)
902 [0-12-816454-9.00009-2](https://doi.org/10.1016/B978-0-12-816454-9.00009-2)
- 903 Sbrana, A., Toccaceli, R. M. (2011). Carta Geologica della Regione Campania in scala 1: 10.000, Foglio 464
904 Isola d’Ischia.
- 905 Scandone, R., Bellucci, F., Lirer, L., & Rolandi, G. (1991). The structure of the Campanian Plain and the
906 activity of the Neapolitan volcanoes (Italy). *Journal of Volcanology and Geothermal Research*, 48(1–
907 2), 1–31. [https://doi.org/10.1016/0377-0273\(91\)90030-4](https://doi.org/10.1016/0377-0273(91)90030-4)
- 908 Scarpati, C., & Perrotta, A. (2012). Erosional characteristics and behavior of large pyroclastic density
909 currents. *Geology*, 40(11), 1035–1038. <https://doi.org/10.1130/G33380.1>
- 910 Scarpati, C., & Perrotta, A. (2016). Stratigraphy and physical parameters of the Plinian phase of the
911 Campanian Ignimbrite eruption. *Bulletin of the Geological Society of America*, 128(7), 1147–1159.

912 <https://doi.org/10.1130/B31331.1>

913 Scarpati, C., Perrotta, A., Lepore, S., & Calvert, A. (2013). Eruptive history of Neapolitan volcanoes :
914 constraints from 40 Ar – 39 Ar dating. *Geological Magazine*, 150(3), 412–425.

915 <https://doi.org/10.1017/S0016756812000854>

916 Scarpati, C., Sparice, D., & Perrotta, A. (2014). A crystal concentration method for calculating ignimbrite
917 volume from distal ash-fall deposits and a reappraisal of the magnitude of the Campanian Ignimbrite.
918 *Journal of Volcanology and Geothermal Research*, 280, 67–75.

919 <https://doi.org/10.1016/j.jvolgeores.2014.05.009>

920 Scarpati, C., Sparice, D., & Perrotta, A. (2015a). Facies variation in the Campanian Ignimbrite. *Rendiconti*
921 *Online Societa Geologica Italiana*, 33, 83–87. <https://doi.org/10.3301/ROL:2015.20>

922 Scarpati, C., Sparice, D., & Perrotta, A. (2015b). The ground layer of the Campanian Ignimbrite: an example
923 of deposition from a dilute pyroclastic density current. *Bulletin of Volcanology*, 77(11).

924 <https://doi.org/10.1007/s00445-015-0985-0>

925 Servizio Geologico d'Italia (1963). Carta geologica d'Italia scala 1:100.000, foglio 174 – Ariano Irpino
926 “*Geological map of Italy at 1:100.000 scale, sheet number 174 – Ariano Irpino*”. Servizio Geologico
927 d'Italia, Rome.

928 Servizio Geologico d'Italia (1965a). Carta geologica d'Italia scala 1:100.000, foglio 185 – Salerno
929 “*Geological map of Italy at 1:100.000 scale, sheet number 185 – Salerno*”. Servizio Geologico d'Italia,
930 Rome.

931 Servizio Geologico d'Italia (1965b). Carta geologica d'Italia scala 1:100.000, foglio 196 – Sorrento
932 “*Geological map of Italy at 1:100.000 scale, sheet number 196 – Sorrento*”. Servizio Geologico
933 d'Italia, Rome.

934 Servizio Geologico d'Italia (1965c). Carta geologica d'Italia scala 1:100.000, foglio 197 – Amalfi
935 “*Geological map of Italy at 1:100.000 scale, sheet number 197 – Amalfi*”. Servizio Geologico d'Italia,
936 Rome.

937 Servizio Geologico d'Italia (1966). Foglio Geologico n°172 - Caserta. *Carta Geologica d'Italia, scala*
938 *1:100.000*, II ediz., Istituto Poligrafico e Zecca dello Stato, Roma.

939 Servizio Geologico d'Italia (1967a). Carta geologica d'Italia scala 1:100.000, fogli 183-184 – Isola di Ischia
940 – Napoli “*Geological map of Italy at 1:100.000 scale, sheet number 183-184 – Isola di Ischia -*
941 *Napoli*”. Servizio Geologico d'Italia, Rome.

942 Servizio Geologico d'Italia (1967b). Carta geologica d'Italia scala 1:100.000, fogli 160 – Cassino
943 “*Geological map of Italy at 1:100.000 scale, sheet number 160 – Cassino*”. Servizio Geologico d'Italia,
944 Rome.

945 Servizio Geologico d'Italia (1971a). Carta geologica d'Italia scala 1:100.000, foglio 171 – Gaeta e Vulcano
946 di Roccamonfina “*Geological map of Italy at 1:100.000 scale, sheet number 171 – Gaeta e Vulcano di*
947 *Roccamonfina*”. Servizio Geologico d'Italia, Rome.

948 Servizio Geologico d'Italia (1971b). Carta geologica d'Italia scala 1:100.000, foglio 161 – Isernia
949 “*Geological map of Italy at 1:100.000 scale, sheet number 161 – Isernia*”. Servizio Geologico d'Italia,
950 Rome.

951 Servizio Geologico d'Italia (1975). Carta geologica d'Italia scala 1:100.000, foglio 173 – Benevento
952 “*Geological map of Italy at 1:100.000 scale, sheet number 173 – Benevento*”. Servizio Geologico
953 d'Italia, Rome.

954 Seymour, K., & Christanis, K. (1995). Correlation of a tephra layer in western greece with a late pleistocene
955 eruption in the campanian province of italy. *Quaternary Research*.
956 <https://doi.org/10.1006/qres.1995.1005>

957 Seymour, K. S., Christanis, K., Bouzinos, A., Papazisimou, S., Papatheodorou, G., Moran, E., & Dénès, G.
958 (2004). Tephrostratigraphy and tephrochronology in the Philippi peat basin, Macedonia, Northern
959 Hellas (Greece). *Quaternary International*, 121(1), 53–65. <https://doi.org/10.1016/j.quaint.2004.01.023>

960 Smith, V. C., Isaia, R., & Pearce, N. J. G. (2011). Tephrostratigraphy and glass compositions of post-15 kyr
961 Campi Flegrei eruptions: Implications for eruption history and chronostratigraphic markers.
962 *Quaternary Science Reviews*, 30(25–26), 3638–3660. <https://doi.org/10.1016/j.quascirev.2011.07.012>

- 963 Smith, V. C., Isaia, R., Engwell, S., & Albert, P. G. (2016). Tephra dispersal during the Campanian
 964 Ignimbrite (Italy) eruption: implications for ultra-distal ash transport during the large caldera-forming
 965 eruption. *Bulletin of Volcanology*, 78(6). <https://doi.org/10.1007/s00445-016-1037-0>
- 966 Sparice, D. (2015). *Definizione delle litofacies e ricostruzione dell'architettura dell'Ignimbrite Campana*.
 967 Università degli Studi di Napoli Federico II.
- 968 Sparks, R. S. J., & Huang, T. C. (1980). The volcanological significance of deep-sea ash layer associated
 969 with ignimbrites. *Geological Magazine*, 117(5), 425–436.
- 970 Sparks, S., Self, S., Grattan, J., Oppenheimer, C., Pyle, D., Rymer, H. (2005). Super- eruptions: global
 971 effects and future threats, *Report of a Geological Society of London Working Group*, (2nd (print)
 972 Edition).
- 973 Sparks, R. S. J., & Walker, G. P. L. (1977). The significance of vitric-enriched air-fall ashes associated with
 974 crystal-enriched ignimbrites. *Journal of Volcanology and Geothermal Research*, 2, 329–341.
- 975 Stuiver, M., Grootes, P. M., & Braziunas, T. F. (1995). The GISP2 $\delta^{18}\text{O}$ Climate Record of the Past 16,500
 976 Years and the Role of the Sun, Ocean, and Volcanoes. *Quaternary Research*, 44, 341–354.
- 977 Tanguy, J. C., Ribière, C., Scarth, A., & Tjetjep, W. S. (1998). Victims from volcanic eruptions: a revised
 978 database. *Bulletin of Volcanology*, 60(2), 137–144. <https://doi.org/10.1007/s004450050222>
- 979 Thordarson, T., & Self, S. (1996). Sulfur, chlorine and fluorine degassing and atmospheric loading by the
 980 Roza eruption, Columbia River Basalt Group, Washington, USA. *Journal of Volcanology and*
 981 *Geothermal Research*, 74, 49–73.
- 982 Thunell, R., Federman, A., Sparks, R. S. J., & Williams, D. (1979). The age, origin, and volcanological
 983 significance of the Y-5 ash layer in the Mediterranean. *Quaternary Research*, 12(2), 241–253.
 984 [https://doi.org/10.1016/0033-5894\(79\)90060-7](https://doi.org/10.1016/0033-5894(79)90060-7)
- 985 Ton-That, T., Singer, B., & Paterne, M. (2001). $^{40}\text{Ar}/^{39}\text{Ar}$ dating of latest Pleistocene (41 ka) marine tephra in
 986 the Mediterranean sea: Implications for global climate records. *Earth and Planetary Science Letters*,
 987 184(3–4), 645–658. [https://doi.org/10.1016/S0012-821X\(00\)00358-7](https://doi.org/10.1016/S0012-821X(00)00358-7)

988 Torrente, M. M., Milia, A., Bellucci, F., & Rolandi, G. (2010). Extensional tectonics in the Campania
989 Volcanic Zone (eastern Tyrrhenian Sea , Italy): New insights into the relationship between faulting
990 and ignimbrite eruptions. *Boll. Soc. Geol. It.*, 129, 297–315. <https://doi.org/10.3301/IJG.2010.07>

991 Upton, J., Cole, P., Shaw, P., Szakacs, A., Seghedi, I. (2002). Correlation of tephra layers found in southern
992 Romania with the Campanian Ignimbrite (~37 ka) eruption. In: *The Quaternary Research Association*
993 *and First Postgraduate Paleo-environmental Symposium*, 36. Amsterdam: Universiteit van Amsterdam.

994 Veres, D., Lane, C. S., Timar-Gabor, A., Hambach, U., Constantin, D., Szakács, A., et al. (2013). The
995 Campanian Ignimbrite/Y5 tephra layer - A regional stratigraphic marker for Isotope Stage 3 deposits in
996 the Lower Danube region, Romania. *Quaternary International*, 293, 22–33.
997 <https://doi.org/10.1016/j.quaint.2012.02.042>

998 Vezzoli, L., Barberi, F. (1988). Progetto finalizzato geodinamica: monografie finali. X: Island of Ischia.
999 *Quaderni de La ricerca scientifica*, (114).

1000 Vitale, S., & Isaia, R. (2014). Fractures and faults in volcanic rocks (Campi Flegrei, southern Italy): Insight
1001 into volcano-tectonic processes. *International Journal of Earth Sciences*, 103(3), 801–819.
1002 <https://doi.org/10.1007/s00531-013-0979-0>

1003 Walker, G. P. L. (1972). Crystal concentration in ignimbrites. *Contributions to Mineralogy and Petrology*,
1004 36(2), 135–146. <https://doi.org/10.1007/BF00371184>

1005 Walker, G. P. L. (1980). The Taupo pumice: product of the most powerful known (ultraplinian) eruption?
1006 *Journal of Volcanology and Geothermal Research*, 8, 69–94.

1007 Walker, G. P. L. (1981). Characteristics of two phreatoplinian ashes, and their water-flushed origin. *Journal*
1008 *of Volcanology and Geothermal Research*, 9(4), 395–407. [https://doi.org/10.1016/0377-](https://doi.org/10.1016/0377-0273(81)90046-9)
1009 [0273\(81\)90046-9](https://doi.org/10.1016/0377-0273(81)90046-9)

1010 Wilson, C. J. N., & Walker, G. P. L. (1985). The Taupo eruption, New Zealand. 1. General aspects.
1011 *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*,
1012 314(1529), 199–228.

1013 Witham, C. S. (2005). Volcanic disasters and incidents: A new database. *Journal of Volcanology and*
1014 *Geothermal Research*, 148(3–4), 191–233. <https://doi.org/10.1016/j.jvolgeores.2005.04.017>

1015 Woods, A. W. (1998). Observations and models of volcanic eruption columns. *Geological Society Special*
1016 *Publication*, 145, 91–114. <https://doi.org/10.1144/GSL.SP.1996.145.01.06>

1017 Woods, A. W., & Wohletz, K. (1991). Dimensions and dynamics of co-ignimbrite eruption columns. *Nature*,
1018 350(6315), 225–227. <https://doi.org/10.1038/350225a0>

1019 Zilhão, J. (2006). Neandertals and moderns mixed, and it matters. *Evolutionary Anthropology*, 15(5), 183–
1020 195. <https://doi.org/10.1002/evan.20110>

1021

Authors	Volume calculations (km ³)					Total
	Plinian fallout	Co-plinian ash	PDC	Co-ignimbrite ash	Y-5	
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*)		
Marti et al., 2016	54 (22.6*)			153.9 (61.6*)		207.9 (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.

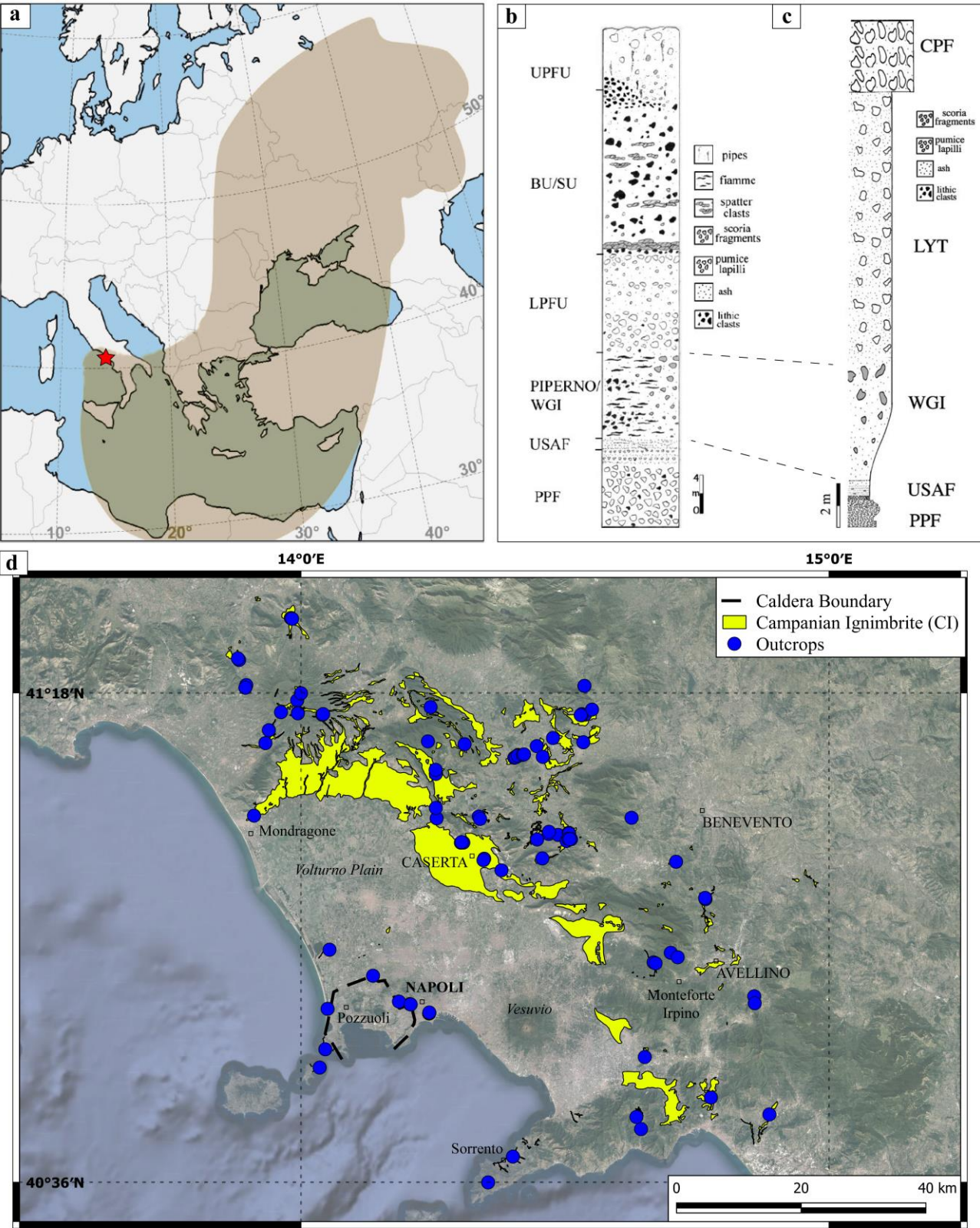
1029

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).*

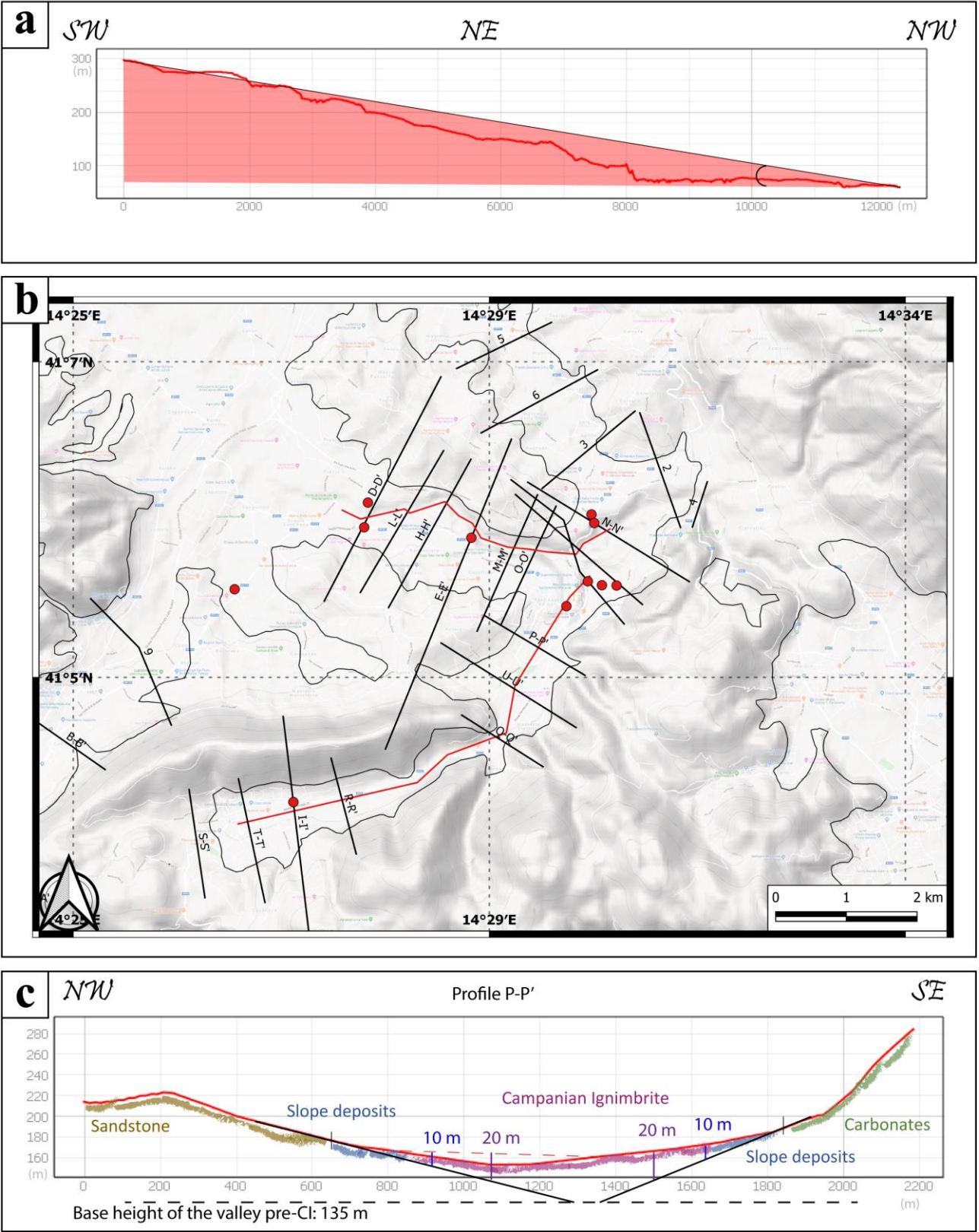
1034



1036

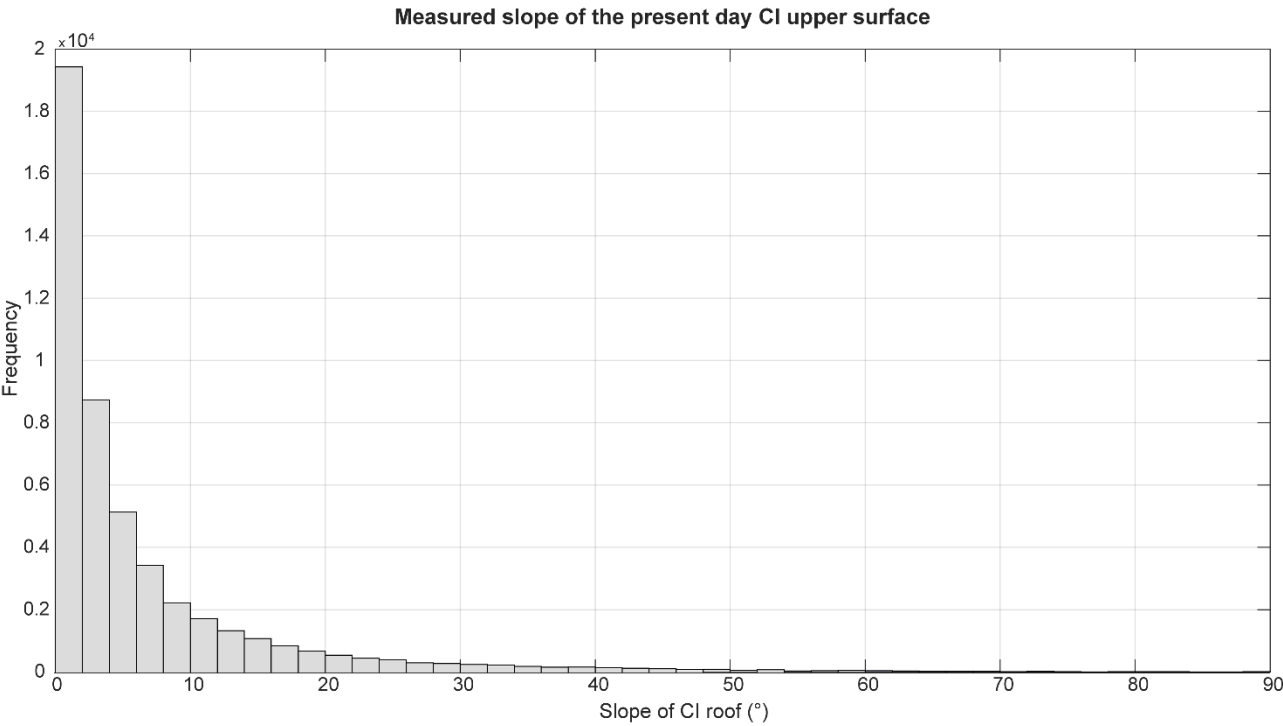
1037 **Figure 1.** The Campanian Ignimbrite distribution. (a) Dispersal area of the CI tephra from the Campi Flegrei
1038 caldera (red star), modified from Giaccio et al. (2017). Stratigraphic type-sections of CI proximal (b) and
1039 distal (c) deposits modified from Fedele et al. (2008) and Cappelletti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



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

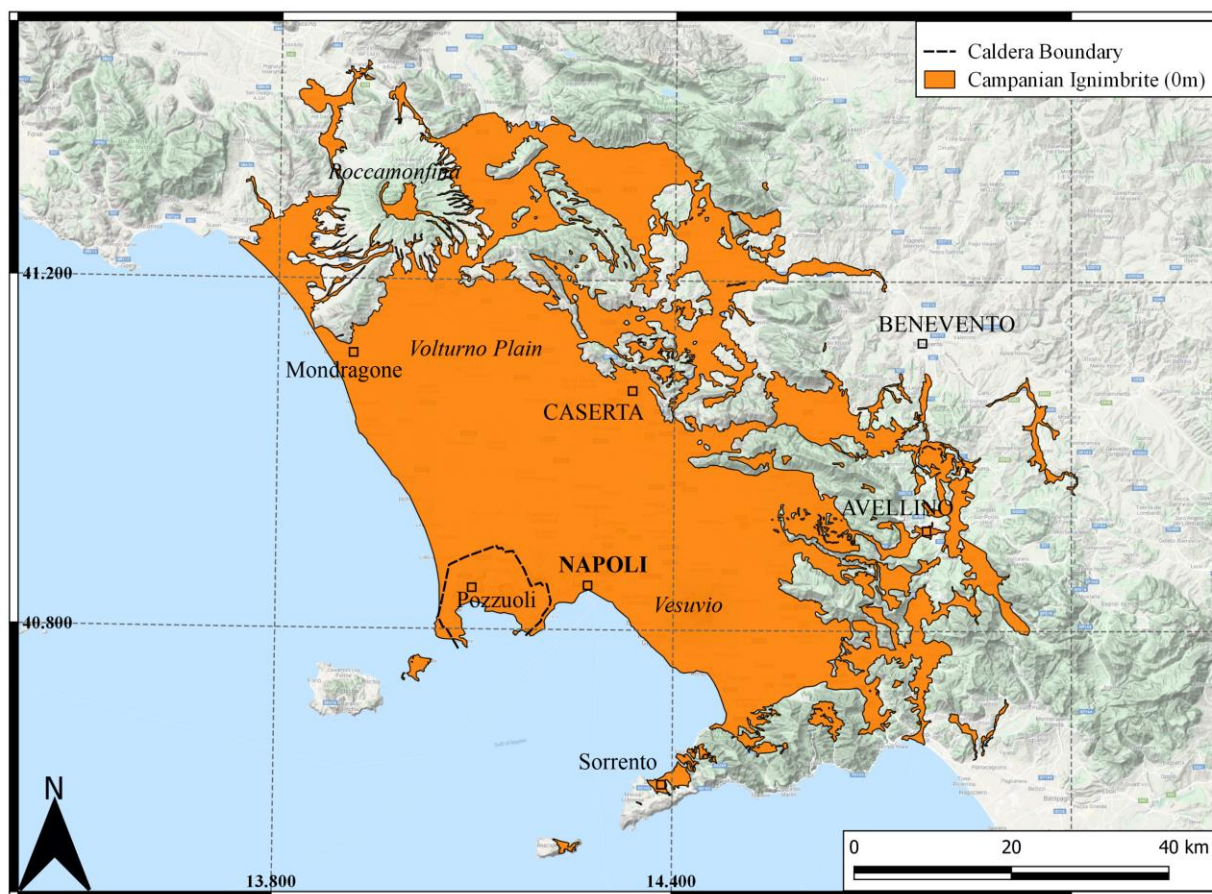
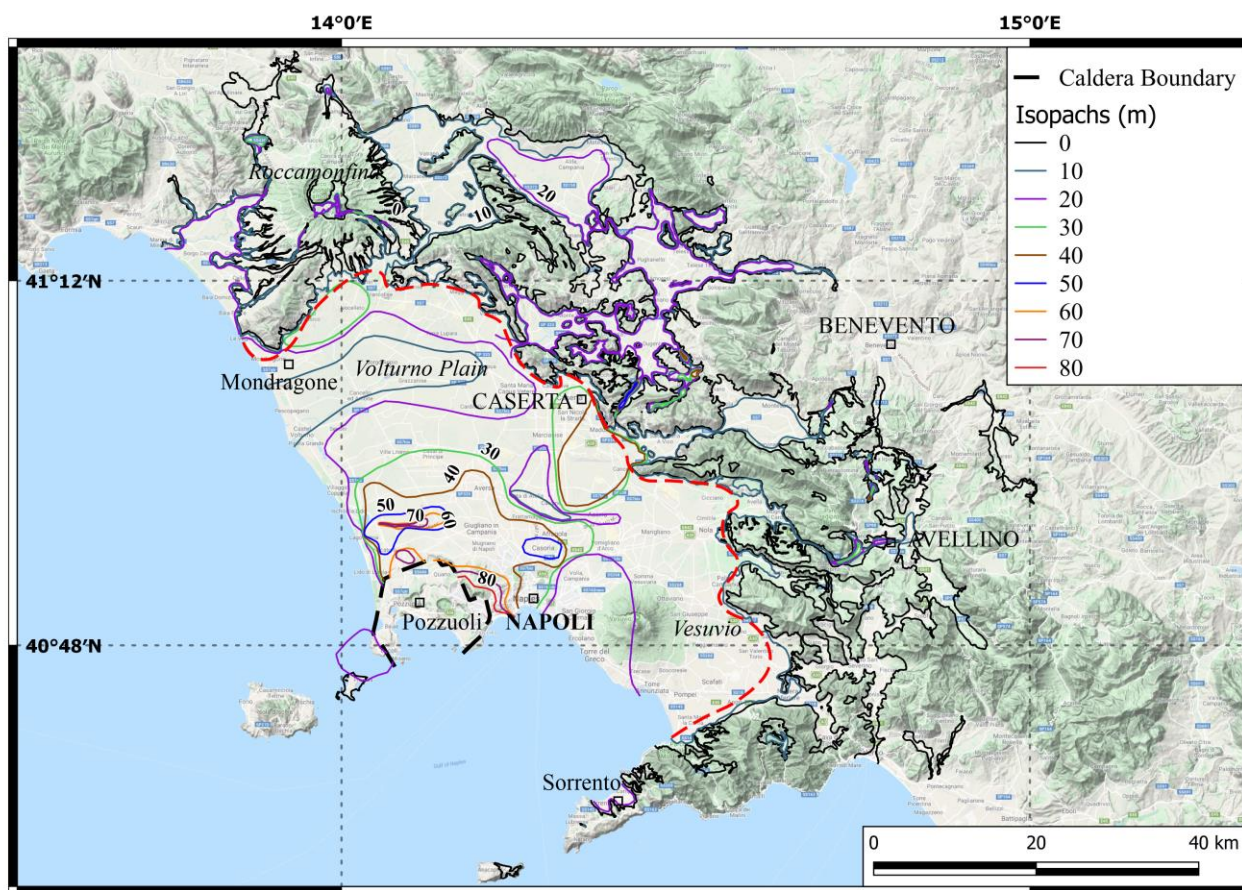


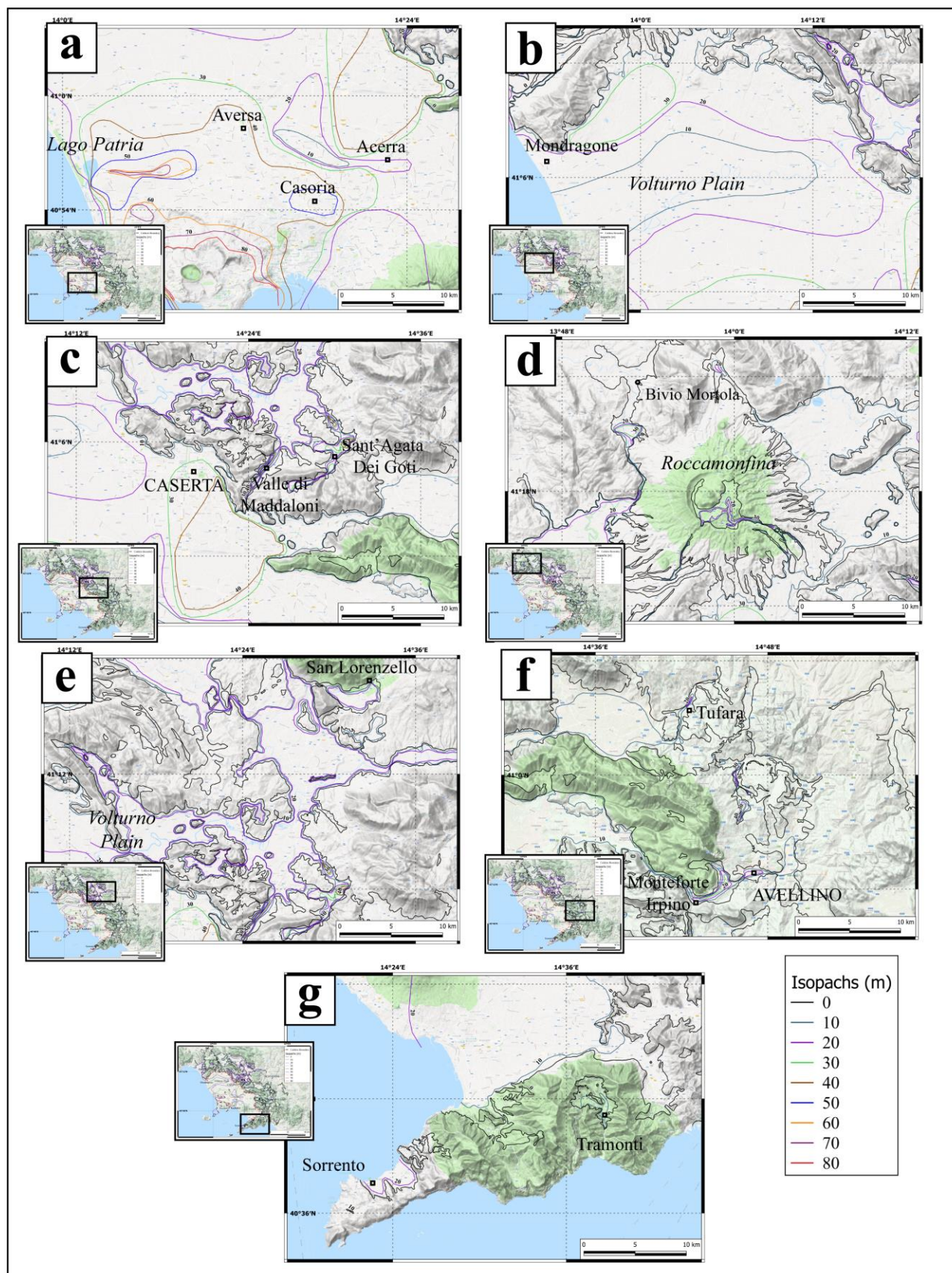
Figure 4. The areal extent of the CI, enclosed within the isopach 0 m is shown in orange. The total area covered by the preserved deposits of CI is 3216 km², the envelopment with a shape is equal to 7547 km².



1060

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

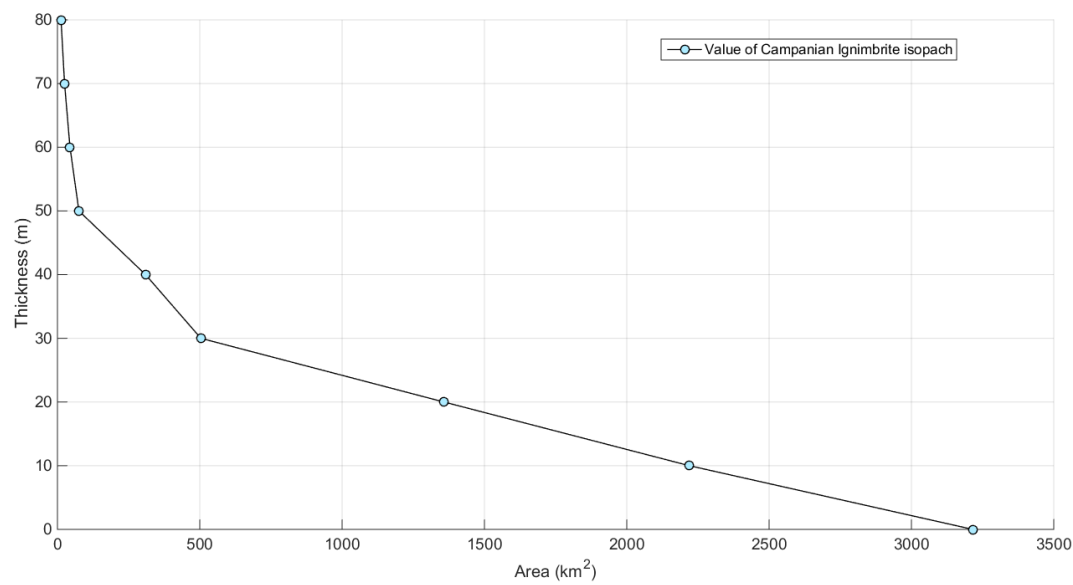


1066

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 Lorenzo 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.

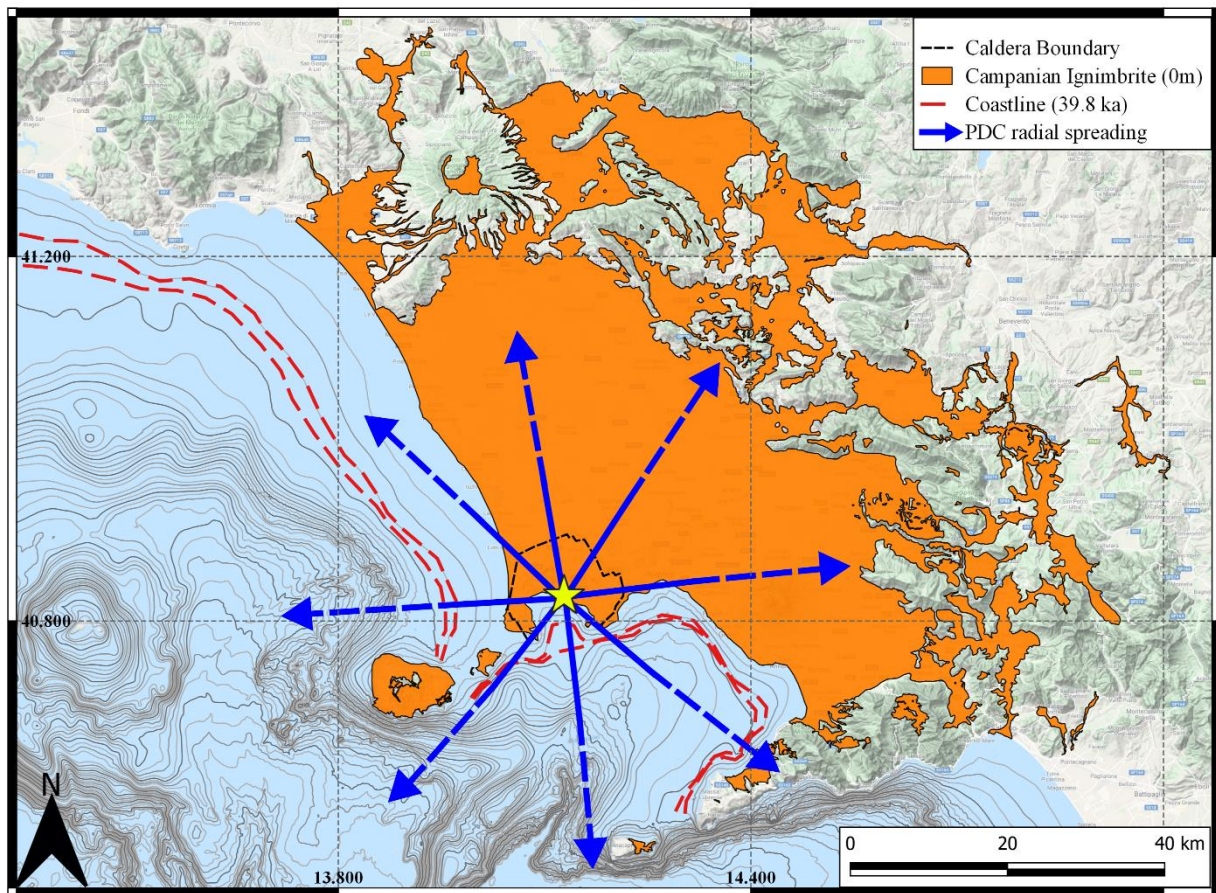
1072



1073

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.

1076



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.

1082