The voulme of the 39.8 ka Campanian Ignimbrite, Italy

Aurora Silleni[1#], Guido Giordano[1], Roberto Isaia[2], Michael H. Ort[3]

 # corresponding author: aurora.silleni@uniroma3.it

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

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

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

Key Points

- The preserved extra-caldera bulk volume of the ignimbrite is 61.5 km^3 ± 5.5 km^3.
- The eruption had a total volume of 164.9 km^3 – 247.7 km^3 DRE and a magnitude of 7.7.
- The volume is essential for climate simulations of Europe during the Pleistocene.

Abstract

The 39.8 ka Campanian Ignimbrite (CI) is the largest caldera-forming eruption of the Campi Flegrei during the Quaternary, which had a global-scale impact on the environment and human populations. The cooling following the eruption and the several effects of it strongly affected the paleoenvironment and the migration of hominids in Europe. The volume of the eruption is necessary to constrain the climate model of this area in the past. However, despite a large number of studies, the Dense Rock Equivalent (DRE) volume estimates range from 60 to 300 km^3. Here we present a review of the previous volume evaluations and a new calculation of the volume of the ignimbrite. This estimate is constrained by an isopach map that reconstructs the paleo-topography during the eruption. The preserved total bulk extra-caldera volume of the ignimbrite is estimated at 61.5 km^3 ± 5.5 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 km^3 – 247.7 km^3 DRE. This value corresponds to a mass of 4.30 - 6.46 x 10^{14} 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.

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 km^3 to 247.7 km^3) and the total mass of magma (4.30 - 6.46 x 10^{14} 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.

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.

Keywords

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

1. Introduction

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

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

The Campanian Ignimbrite (CI; Barberi et al., 1978; De Vivo et al., 2001; Fedele et al., 2008; Fisher et al., 1993) is associated with the most powerful caldera-forming eruption from Campi Flegrei (Fig. 1a) (Rosi & Sbrana, 1987; Perrotta et al., 2006; Scarpati et al., 2013), which occurred at 39.8 ka (Giaccio et al., 2017). It is one of the largest late Quaternary explosive events and has been considered as an example of a super-eruption (Sparks et al., 2005). The CI tephra represents the most widespread volcanic deposit and one of the most important temporal/stratigraphic markers for the Early Upper Paleolithic of western Eurasia (F. G. Fedele et 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 km^3, 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 &

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

The CI eruption emplaced both pyroclastic fall and PDC deposits in a complex sequence currently exposed in proximal, medial, distal and ultra-distal outcrops (Fig. 1) (Barberi et al., 1978; Cappelletti et al., 2003; Engwell et al., 2014; L. Fedele et al., 2008; Fisher et al., 1993; Orsi et al., 1996; Perrotta et al., 2006; Perrotta & Scarpati, 1994, 2003; Rosi et al., 1988, 1996, 1999; Scarpati et al., 2015a, 2015b; Scarpati & Perrotta, 2016; Smith et al., 2016; Sparice, 2015; De Vivo et al., 2001). The first phase of the eruption generated a Plinian column up to 44 km high (Marti et al., 2016; Rosi et al., 1999), producing a widespread fall deposit dispersed by winds to the east (Marti et al., 2016; Perrotta & Scarpati, 2003; Rosi et al., 1999; Scarpati & Perrotta, 2016). A pyroclastic density current then spread over an area of 7,000 km^2 and surmounted ridges more than 1,000 m high (Barberi et al., 1978; Fisher et al., 1993). This stage caused the caldera collapse and the accumulation of lithic breccia's deposits (Breccia Museo) in scattered outcrops along the caldera rim (L. Fedele et al., 2008; Melluso et al., 1995; Perrotta & Scarpati, 1994; Rosi et al., 1996). In distal outcrops, most of the CI is represented by a massive, gray ignimbrite (Barberi et al., 1978; Fisher et al., 1993; Scarpati et al., 2015a; Scarpati & Perrotta, 2012). In more distal and ultra-distal sites deposits are made up by coarse to fine ash containing both co-plinian and co-ignimbrite tephra (Engwell et al., 2014; Smith et al., 2016; Sparks & Huang, 1980; Thunell et al., 1979). The tephra marker related to this eruption is essential to correlate volcanological and archeological sites in the Mediterranean area and Eastern Europe. Tephra-based correlations of human sites were used to date the Middle to Upper Paleolithic transition (Lowe et al., 2012).

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

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

3. The previous estimates of the CI volume

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

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

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

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

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

All these four factors were calculated during the last forty years by different authors and with different methods (Table 1), resulting in final dense rock equivalent (DRE) volume estimates ranging from 60 to 300 km^3 (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).

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

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

The first volume estimate of the ignimbrite was presented by Thunell et al. (1979). Based on a geometrical method that considers a covered area of over 6000 km^2 with a thickness up to 100 m and assuming a radial flow of the PDC, they estimate the DRE volume is at least 30-40 km^3. The DRE volume of the Y-5 ash layer within the 1-cm isopach contour was also estimated at 30-40 km^3 (65 km^3 bulk) and the authors recognized that Y-5 is composed by a co-plinian and a co-ignimbrite ash, but they did not calculate each contribution to the volume. Their total DRE volume is 60-80 km^3 for the eruption.

Cornell et al. (1983) calculated the ash-fall layer volume of Y-5 from an isopach map derived by different cores drilled in the Mediterranean Sea (73 km^3 bulk). They then included the ignimbrite DRE volume proposed by Thunell et al. (1979) in their overall eruption volume estimate.

Fisher et al. (1993) estimated a bulk volume of the original pyroclastic current of about 500 km^3 by circumscribing a circle of deposits with a radius of 100 km, 100 m thick at the center that thinned to zero at the perimeter of the circle.

Civetta et al. (1997) is one of the first works that subdivided the volume of the CI based on the pumice composition. The authors divided the magma into three different types: a most evolved one that consists of Plinian fallout and some ignimbrite up to 50 km from the vent (a volume of 25 km^3 DRE), a magma with intermediate composition that includes some of the ignimbrite out to its farthest extent (100 km^3 DRE), and a least-evolved magma that includes much of the ignimbrite in the Campanian Plain (20 km^3 DRE). All the volume calculations were made by circumscribing circles with a radius similar to the maximum distance reached from the vent by that magma type and a thickness that goes from the maximum thickness of ignimbrite of that composition at the caldera center to zero at the perimeter of the circle.

Pappalardo et al. (2008) used petrological data to constrain the pre-eruptive magma storage dynamics and, in agreement with Civetta et al. (1997), proposed a total volume of 200 km^3 DRE (20 km^3 for the fallout and 180 km^3 for the ignimbrite).

Rosi et al. (1999) calculated the bulk volume of the Plinian fallout as 15 km^3 based on the method proposed by Pyle (1989), which assumes exponential thickness decay away from the vent and an elliptical isopach distribution with the source at one focus; in the CI case, this focus corresponds to a central vent, located in the Campi Flegrei caldera center (town of Pozzuoli). The same technique was used by Perrotta and Scarpati (2003), who estimated a bulk volume of 4.03 km^3, the different value being the result of a different way than Rosi et al. (1999) used to trace the isopach lines. In the same work, the authors attempt, for the first time, to discriminate between the co-plinian and co-ignimbrite components. The coarse ash of ultra-distal deposits was interpreted as the co-plinian phase, while the fine ash represents the co-ignimbrite component. The authors evaluated the thicknesses of the two parts and estimated the volume as follows: 16 km^3 of co-plinian ash and 100 km^3 of co-ignimbrite ash. Scarpati and Perrotta (2016) subdivided the fallout into five layers (A to E) and calculated the volumes for each of them using the same exponential fitting, obtaining a primary fallout of 5.33 km^3 (0.88 km^3 DRE) and a co-plinian ash of 14.67 km^3 (6.88 km^3 DRE).

These analyses were improved upon by Pyle et al. (2006), who estimated the minimum bulk volume of the CI fallout of 74 km^3 or 31 km^3 DRE: the authors used the general observation that many fallout deposits show exponential decay of thickness (Pyle, 1989) and formulated that the total volume of the exponentially thinning sheet is equal to $13.08 T_0 b_t^2$ (T_0 is the maximum thickness at source and b_t is the linear distance over which the isopach thickness falls by a half). In the same work, the authors compared these results with a second approach based on the rate of thinning of the distal ash sheets (Pyle, 1989, 1990): given that the thickest ash layer in marine cores is of the order of 10–20 cm, it is most likely that the total bulk ash volume associated with the eruption was in the range 74-120 km^3 (31–50 km^3 DRE) (Pyle et al., 2006).

A first attempt to compare all the volume estimates was proposed by Fedele et al. (2003), who considered the sum of the conservative estimates reported in literature. The total DRE volume they proposed is 200 km^3 (the sum of the fallout, the PDC deposits and the Y-5 ash layer volumes (Civetta et al., 1997; Rosi et al., 1999; Thunell et al., 1979)).

Giaccio (2006) calculated the volume of the PDC using a complex truncated cone, with a concave surface and 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 km. The volume obtained is 385 km^3 (215 km^3 DRE). At the same time, he proposed a revised isopach map for the fallout deposits, resulting in a volume estimate of 10 km^3 (3 km^3 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 km^3 (86 km^3 DRE). He thus estimated a bulk volume of 575 km^3 (300 km^3 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 km^3 (104-125 km^3 DRE) and a total volume of the eruption of 430-680 km^3 (180-280 km^3 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 km^3 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:

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

The bulk volume of the PDC deposits thus estimated is 54 km^3 (25 km^3 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 km^3 (22.6 km^3 DRE) and the co-ignimbrite bulk volume is 153.9 km^3 (61.6 km^3 DRE), for a bulk total volume of 207.9 km^3 (84.2 km^3 DRE).

To summarize, the existing estimates of the total DRE volume of the CI eruption range from 60 to 300 km^3 (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) and those for the bulk volume of the CI pyroclastic density current deposits range between 54 and 500 km^3 (Civetta et al., 1997; Cornell et al., 1983; Fisher et al., 1993; Marianelli et al., 2006; Pappalardo et al., 2008; Rolandi et al., 2003; Scarpati et al., 2014; Thunell et al., 1979). The margin of error in these volumes is unacceptably high due to the different methods used, especially in view of the relevance of such figures on the impact on climate and the environment. While the computational methods for the fallout deposits have improved significantly in the past ten years and the related figures for the fallout phase appear strong and solidly based on field data (Costa et al., 2012; Marti et al., 2016), the volume figures for the CI ignimbrite appear to remain very poorly constrained, although this volume largely affects the estimation of the volume of elutriated co-ignimbrite ash, which is the dominant fallout phase across Europe and the most relevant fraction of ash injected into the stratosphere at the time of the eruption (e.g. Costa et al., 2018).

4. The making of the CI isopach map

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

4.1 Database and fieldwork

Published data regarding CI thickness and outcrop locations were collected from 42 papers (presented in Data Repository, Table 1). The whole data were inserted in a GIS Open-Source QGIS 3.4 (https://www.qgis.org/it/site/) database including 238 localized outcrops. The database includes the name of the location, the lithological description, the geographic coordinates, the elevation a.s.l., the thickness of the flow units (specifying whether total or outcrop thickness), the maximum lithic dimensions and the degree of welding. Where both base and top of the CI are exposed, the thickness is classified as total and elsewhere it is considered a minimum thickness.

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

4.2 The zero-thickness isopach

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

4.3 The isopachs

To determine the isopach locations, two different methods were used, one in the proximal area (from the caldera to the base of the Apennine Mountains, including the Campanian Plain) and one in the more distal area. The almost complete lack of outcrops in the Campanian Plain and the valley-ponded depositional style in the ridge-valley topography of the Apennine Mountains (L. Fedele et al., 2016; Langella et al., 2013; Perrotta et al., 2010; Rosi et al., 1983, 1996; Scarpati et al., 2014, 2015a; Sparice, 2015) make these different approaches necessary.

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

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

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

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

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

5. Results

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

5.1 The isopach maps

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

Based on these results, the 0-m isopach was traced to enclose all the mapped CI and areas that probably have the CI below the recent sedimentary cover and have a slope less than 15°. The total area enclosed by the 0-m isopach of the CI is 3216 km^2 (Fig. 4). To understand also the total area of the region involved in the PDC, a shape was drawn comprising all the areal extension of the isopach 0-m. The enveloped area is equal to 7547 km^2, similar to the 7000 km^2 estimate (Barberi et al., 1978).

The isopach map traced in the proximal area does not include the intracaldera deposits. The maximum thickness in proximal areas is 80 m (Fig. 5), mainly based on outcrops near the caldera rim; the CI thins gradually away from the caldera margin. Two areas of thickening are identified just north of the caldera and 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 (down to 10 m) are recognized to the north in the Campanian Plain (Fig. 6b), in the area between Aversa and Acerra and in the south of the Campanian Plain (Fig. 6a).

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

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

5.2 Density of the CI deposits

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

The bulk density (ρ) of the WGI samples from the Campanian Plain ranges from 0.745 ± 0.015 g/cm^3 to 1.330 ± 0.003 g/cm^3, with an average at 0.980 ± 0.011 g/cm^3. The bulk density of the Piperno unit ranges from 1.275 ± 0.008 g/cm^3 to 1.302 ± 0.002 g/cm^3, with an average of 1.287 ± 0.004 g/cm^3 (presented in Data Repository, Table 3). Open porosity was estimated with geometric (V_g) and matrix volume (V_m): $100*(V_g-V_m)/V_g$, while closed porosity was determined using the DRE of the WGI and Piperno powder, which was obtained by the pycnometer. The total WGI porosity (φ_t) was calculated directly adding up closed and open porosity and it ranges from 49 ± 5% and 71± 5% and the average is 61.6% ± 5%, for the Piperno unit it is 50 ± 1%. The ρ DRE is 2.6077 ± 0.0031 g/cm^3. The DRE volume is determined multiplying the bulk volume by (100- φ_t)/100.

5.3 Deposits volume calculation

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

The total volume of the preserved extra-caldera CI deposits on land is 61.5 km^3 ± 5.5 km^3 (22.0 ± 2.2 km^3 DRE).

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

A recent study proposed contour maps of the lower and the upper surfaces of the CI for the north-western sector of the proximal area, based on 1000 of lithostratigraphic logs from boreholes (Ruberti et al., 2020). The difference of the upper surface and the lower one is the CI thickness, which is not reported on the work of Ruberti et al. (2020). The extrapolated thicknesses from the maps were compared with the isopach map of the proximal area of this work and it shown great similarities in the areas of Mondragone, Caserta and Lago Patria. On the other hand, there are some differences of the thicknesses in the Volturno Plain, where the authors suggest a thicker CI. To evaluate these discrepancies, a new proximal isopach map was drawn taking into consideration the new thickness data. The volume related to this map is 46.7 km^3, meaning a difference of 0.3 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 uncertainties in the proximal area. For this reason, the data proposed by Ruberti et al. (2020) were not inserted in the isopach map reported in this work, however, a greater thickness in the Volturno Plain could be considered, even though it doesn’t change the final total volume of the proximal area and of all the CI.

6. The volume of the Campanian Ignimbrite

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

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

6.1 Extracaldera volume

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

The reconstructed isopachs do not consider the linear erosion due to river incision of the CI so the possible areal erosion must be calculated. The linear erosion is referred to the selective erosion due to rivers, while the areal erosion comprises all the regional processes that occurred in the area. The deposits of WGI show a mainly valley-ponded deposit pattern; in many areas where the ignimbrite was deposited in narrow valleys (for instance near Roccamonfina), the only unit that mantles the topography is USAF, while the upper surface of WGI is mainly horizontal (Fig. 3) (Sparice, 2015). This suggests that USAF is a facies emplaced in a wider area distribution than WGI, comprising also topological highs with mantling features. The thickness of USAF is mainly between 10 cm and 1 m and, in rare cases, it can reach 3 m (L. Fedele et al., 2016). A median thickness of 1 m is assumed as eroded material for all the enveloped area (7547 km^2, projected area) not covered by valley-pond facies, as a reference for the areal erosion. From a DEM, the real surface enveloped area was computed at 9575 km^2, meaning the calculation of the area on the DEM and not on a projected horizontal surface, it was so evaluated also the deposition on mountain slope (as a mantling feature deposition). The volume associated with the areal erosion is 9.6 km^3 (V_e) (3.7 km^3 DRE, using the average density of WGI). This is a correction based on field observation (USAF able to mantling the topography) and an average calculation (the thickness and the area), obviously, it is just a reference value, and could vary if the eroded thickness, or involved area, are considered substantially different.

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

The presence of the turbidity currents in the Mediterranean basin and coeval to the eruption was confirmed by the analyses of the core CT85-5 in the Tyrrhenian Sea (40°19’02’’N, 11°15’42’’E) located more than 200 km west from the CF caldera (Castagnoli et al., 1995; Giaccio, 2006; Giaccio et al., 2006; Hajdas et al., 2011). The CI tephra recognized within the core was used as an important time marker and it is 45 cm thick. The nearby CT85-6 confirmed the presence of the CI tephra, however, it was less studied as its record is shorter and the CI is not reported fully (Hajdas et al., 2011). In the CI layer, were found shallow water gastropods and internal lamination, which indicate that at least 10 cm of the section are from turbiditic origin (Castagnoli et al., 1995; Giaccio, 2006; Hajdas et al., 2011). These volcanoclastic currents related to the CI eruption are strongly reported in all the Tyrrhenian basin (Giaccio, 2006; McCoy & Cornell, 1990) interpreted as a large syn-eruptive phenomena of the CI deposits, triggered by the PDCs which entered inside the water and in general to the volcanic event. The turbidity currents can be reasonably considered as primary products of the eruption (Giaccio, 2006).

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

6.2 Intracaldera volume

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

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

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

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

6.3 Distal tephra volume

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

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

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

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

The first work that attributed a volume to the two components was presented by Perrotta and Scarpati (2003). The method used by the authors was previously explained. At a later time, Marti et al. (2016) modelled the CI tephra dispersion and gave a volume estimation of the two phases. They recognized the great impacts of the tephra fallout in the westward migration of modern hominid groups in Europe. Moreover, they supported the hypothesis that Neanderthals populations persisted in southern Europe after the CI eruption, especially in southern Iberia (Zilhão, 2006).

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

6.4 The volume, mass and magnitude of the CI

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

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

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

and

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

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

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

The co-ignimbrite volume, using a vitric loss of 0.65, ranges between 273.4 km^3 and 364.7 km^3 (107.6 km^3 – 143.5 km^3 DRE). However, V_{ci} could change a lot, according to the value of vitric loss used. From the literature, Walker (1972) proposed for the outcrop of Altavilla (WGI), near Benevento, a vitric loss of 0.55. Using this data, the co-ignimbrite bulk volume decreases and it is substantially lower between 168.2 km^3 and 240.0 km^3. It is necessary great attention to the right value of vitric loss to use, which can significantly influence the total eruptive volume. In this work, we use 0.65, proposed by Scarpati et al. (2014), which is an average of more samples located in several sites all over the CI distribution and from different units (WGI, LYT and CPF). Moreover, it is not quite far from 0.55 previously proposed in literature (Walker, 1972) and the co-ignimbrite volume obtained agrees with the one proposed by Costa et al. (2012) (250 - 300 km^3) using the fit of an advection – diffusion tephra dispersion model to thickness data.

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

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

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

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

And (8)

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

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

$$M\ = log10(mass) - 7 = 7.7 \quad \text{[Eq. 9]}$$

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 ~6-9°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 km^3 ± 5.5 km^3. The greater part of this volume is in the proximal area (46.4 ± 1.6 km^3, ~75%) while only around the 25% of the volume is in the distal region after the Apennines Mountain (15.1 ± 3.9 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 km^3 – 225.1 km^3 DRE), values in agreement with Giaccio (2006) and Pappalardo et al. (2008).

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

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

Acknowledgments and Data

AS and GG gratefully acknowledge The Grant of Excellence Departments, MIUR-Italy. AS thanks Emanuele Sciarrino and Rose Gallo for their help in the fieldwork. We thank Danilo M. Palladino for discussions. Partial support for some field costs was provided by NSF EAR1761713 to MHO. The data presented here are available in Data Repository, online at https://mfr.osf.io/render?url=https%3A%2F%2Fosf.io%2F3a6bz%2Fdownload.

CRediT authorship contribution statement

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

References

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

Albert, P. G., Giaccio, B., Isaia, R., Costa, A., Niespolo, E. M., Nomade, S., et al. (2019). Evidence for a large-magnitude eruption from Campi Flegrei caldera (Italy) at 29 ka. *Geology*, *47*(7), 595–599. https://doi.org/10.1130/G45805.1

Allen, S. R., & Cas, R. A. F. (2001). Transport of pyroclastic flows across the sea during the explosive, rhyolitic eruption of the Kos Plateau Tuff, Greece. *Bulletin of Volcanology*, *62*(6–7), 441–456. https://doi.org/10.1007/s004450000107

Anikovich, M., Sinitsyn, A. A., Hoffecker, J. F., Holliday, V. T., Popov, V. V., Lisitsyn, S. N., et al. (2007). Early Upper Paleolithic in Eastern Europe and Implications for the Dispersal of Modern Humans. *Science*, *315*(5809), 223–226. https://doi.org/10.1126/science.1133376

Antonioli, F. (2012). Sea level change in Western-Central Mediterranean since 300 kyr: Comparing global sea level curves with observed data. *Alpine and Mediterranean Quaternary*, *25*(1), 15–23.

Antonioli, F., Bard, E., Potter, E. K., Silenzi, S., & Improta, S. (2004). 215-ka history of sea-level oscillations from marine and continental layers in Argentarola Cave speleothems (Italy). *Global and Planetary Change*, *43*(1–2), 57–78. https://doi.org/10.1016/j.gloplacha.2004.02.004

Barberi, F., Innocenti, F., Lirer, L., Munno, R., Pescatore, T., & Santacroce, R. (1978). The campanian ignimbrite: a major prehistoric eruption in the Neapolitan area (Italy). *Bulletin Volcanologique*, *41*(1), 10–31. https://doi.org/10.1007/BF02597680

Barsotti, S., Neri, A., & Scire, J. S. (2008). The VOL-CALPUFF model for atmospheric ash dispersal: 1. Approach and physical formulation. *Journal of Geophysical Research: Solid Earth*, *113*(3), 1–12. https://doi.org/10.1029/2006JB004623

Bellucci, F. (1994). Nuove conoscenze stratigrafiche sui depositi vulcanici del sottosuolo del settore meridionale della piana campana. *Boll. Soc. Geol. It.*, *113*, 395–420.

Black, B. A., Neely, R. R., & Manga, M. (2015). Campanian Ignimbrite volcanism, climate, and the final decline of the Neanderthals. *Geology*, *43*(5), 411–414. https://doi.org/10.1130/G36514.1

Bonadonna, C., & Phillips, J. C. (2003). Sedimentation from strong volcanic plumes. *Journal of Geophysical*

Research: Solid Earth, *108*(B7), 1–28. https://doi.org/10.1029/2002jb002034

Bonadonna, C., Ernst, G. G. J., & Sparks, R. S. J. (1998). Thickness variations and volume estimates of tephra fall deposits: the importance of particle Reynolds number. *Journal of Volcanology and Geothermal Research*, *81*(3–4), 173–187. https://doi.org/10.1016/S0377-0273(98)00007-9

Bonadonna, C., Connor, C. B., Houghton, B. F., Connor, L., Byrne, M., Laing, A., & Hincks, T. K. (2005). Probabilistic modeling of tephra dispersal: Hazard assessment of a multiphase rhyolitic eruption at Tarawera, New Zealand. *Journal of Geophysical Research: Solid Earth*, *110*(3), 1–21. https://doi.org/10.1029/2003JB002896

Bluszcz, A., Hercman, H., Pazdur, A., Pazdur, M. (1992). Radiometric dating. In *Temnata Cave. Excavations in Karlukovo Karst Area, Bulgaria*, vol. 1.1, ed. By J.K. Kozlowski, H. Laville and B. Ginter, pp. 223-240. Cracow: Jagellonian University Press.

Capocci, E. (1835). Nuove ricerche sul noto fenomeno delle colonne perforate dale Foladi nel tempio di Serapide in Pozzuoli.

Cappelletti, P., Cerri, G., Colella, A., de'Gennaro, M., Langella, A., Perrotta, A., & Scarpati, C. (2003). Post-eruptive processes in the Campanian Ignimbrite. *Mineralogy and Petrology*, *79*(1–2), 79–97. https://doi.org/10.1007/s00710-003-0003-7

Carey, S., Sigurdsson, H., Mandeville, C., & Bronto, S. (1996). Pyroclastic flows and surges over water: an example from the 1883 Krakatau eruption. *Bulletin of Volcanology*, *57*(7), 493–511. https://doi.org/10.1007/BF00304435

Cashman, K. V., & Giordano, G. (2014). Calderas and magma reservoirs. *Journal of Volcanology and Geothermal Research*, *288*, 28–45. https://doi.org/10.1016/j.jvolgeores.2014.09.007

Castagnoli, G. C., Albrecht, A., Beer, J., Shen, C., Callegari, E., Taricco, C., et al. (1995). Evidence for enhanced 10Be deposition in Mediterranean sediments 35 Kyr BP. *Geophysical Research Letters*, *22*(6), 707–710.

Civetta, L., Orsi, G., Pappalardo, L., Fisher, R. V., Heiken, G., & Ort, M. H. (1997). Geochemical zoning, mingling, eruptive dynamics and depositional processes - the Campanian Ignimbrite, Campi Flegrei caldera, Italy. *Journal of Volcanology and Geothermal Research*, *75*, 183–219.

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

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

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

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

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

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

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

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

0397-z

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

ISPRA (2018). Geological Map n. 464 ‘‘Isola d’Ischia’’; scale 1:25,000. *National Geological Survey of Italy*, Regione Campania, Settore Difesa Suolo, Napoli, Italy.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Perrotta, A., & Scarpati, C. (2003). Volume partition between the plinian and co-ignimbrite air fall deposits of the Campanian Ignimbrite eruption. *Mineralogy and Petrology*, *79*(1–2), 67–78. https://doi.org/10.1007/s00710-003-0002-8

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

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

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

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

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

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

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

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

Rosi, M., Sbrana, A. (1987). Phlegrean Fields. CNR, *Quaderni de La ‘‘Ricerca Scientifica’’* 114, 1–175.

Rosi, M., Sbrana, A., & Principe, C. (1983). The phlegraean fields: Structural evolution, volcanic history and eruptive mechanisms. *Journal of Volcanology and Geothermal Research*, *17*(1–4), 273–288. https://doi.org/10.1016/0377-0273(83)90072-0

Rosi, M., Sbrana, A., & Vezzoli, L. (1988). Correlazioni tefrostratigrafiche di alcuni livelli di Ischia, Procida e Campi Flegrei. *Memorie Della Società Geologica Italiana*, *41*, 1015–1027.

Rosi, M., Vezzoli, L., Aleotti, P., & Censi, M. (1996). Interaction between caldera collapse and eruptive dynamics during the Campanian Ignimbrite eruption, Phlegraean Fields, Italy. *Bulletin of Volcanology*, *57*(7), 541–554. https://doi.org/10.1007/BF00304438

Rosi, M., Vezzoli, L., Castelmenzano, A., & Grieco, G. (1999). Plinian pumice fall deposit of the Campanian Ignimbrite eruption (Phlegraean Fields, Italy). *Journal of Volcanology and Geothermal Research*, *91*(2–4), 179–198. https://doi.org/10.1016/S0377-0273(99)00035-9

Ruberti, D., Vigliotti, M., Rolandi, R., & Lascio, M. Di. (2020). Effect of paleomorphology on facies distribution of the Campania Ignimbrite in the northern Campania Plain, southern Italy. In *Vesuvius, Campi Flegrei, and Campanian Volcanism* (pp. 207–229). Elsevier Inc. https://doi.org/10.1016/B978-0-12-816454-9.00009-2

Sbrana, A., Toccaceli, R. M. (2011). Carta Geologica della Regione Campania in scala 1: 10.000, Foglio 464 Isola d’Ischia.

Scandone, R., Bellucci, F., Lirer, L., & Rolandi, G. (1991). The structure of the Campanian Plain and the activity of the Neapolitan volcanoes (Italy). *Journal of Volcanology and Geothermal Research*, *48*(1–2), 1–31. https://doi.org/10.1016/0377-0273(91)90030-4

Scarpati, C., & Perrotta, A. (2012). Erosional characteristics and behavior of large pyroclastic density currents. *Geology*, *40*(11), 1035–1038. https://doi.org/10.1130/G33380.1

Scarpati, C., & Perrotta, A. (2016). Stratigraphy and physical parameters of the Plinian phase of the Campanian Ignimbrite eruption. *Bulletin of the Geological Society of America*, *128*(7), 1147–1159.

https://doi.org/10.1130/B31331.1

Scarpati, C., Perrotta, A., Lepore, S., & Calvert, A. (2013). Eruptive history of Neapolitan volcanoes : constraints from 40 Ar – 39 Ar dating. *Geological Magazine*, *150*(3), 412–425. https://doi.org/10.1017/S0016756812000854

Scarpati, C., Sparice, D., & Perrotta, A. (2014). A crystal concentration method for calculating ignimbrite volume from distal ash-fall deposits and a reappraisal of the magnitude of the Campanian Ignimbrite. *Journal of Volcanology and Geothermal Research*, *280*, 67–75. https://doi.org/10.1016/j.jvolgeores.2014.05.009

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

Scarpati, C., Sparice, D., & Perrotta, A. (2015b). The ground layer of the Campanian Ignimbrite: an example of deposition from a dilute pyroclastic density current. *Bulletin of Volcanology*, *77*(11). https://doi.org/10.1007/s00445-015-0985-0

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

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

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

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

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

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

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

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

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

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

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

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

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

Smith, V. C., Isaia, R., Engwell, S., & Albert, P. G. (2016). Tephra dispersal during the Campanian Ignimbrite (Italy) eruption: implications for ultra-distal ash transport during the large caldera-forming eruption. *Bulletin of Volcanology*, *78*(6). https://doi.org/10.1007/s00445-016-1037-0

Sparice, D. (2015). *Definizione delle litofacies e ricostruzione dell'architettura dell'Ignimbrite Campana*. Università degli Studi di Napoli Federico II.

Sparks, R. S. J., & Huang, T. C. (1980). The volcanological significance of deep-sea ash layer associated with ignimbrites. *Geological Magazine*, *117*(5), 425–436.

Sparks, S., Self, S., Grattan, J., Oppenheimer, C., Pyle, D., Rymer, H. (2005). Super- eruptions: global effects and future threats, *Report of a Geological Society of London Working Group*, (2nd (print) Edition).

Sparks, R. S. J., & Walker, G. P. L. (1977). The significance of vitric-enriched air-fall ashes associated with crystal-enriched ignimbrites. *Journal of Volcanology and Geothermal Research*, *2,* 329–341.

Stuiver, M., Grootes, P. M., & Braziunas, T. F. (1995). The GISP2 $\delta^{18}O$ Climate Record of the Past 16,500 Years and the Role of the Sun, Ocean, and Volcanoes. *Quaternary Research*, *44*, 341–354.

Tanguy, J. C., Ribière, C., Scarth, A., & Tjetjep, W. S. (1998). Victims from volcanic eruptions: a revised database. *Bulletin of Volcanology*, *60*(2), 137–144. https://doi.org/10.1007/s004450050222

Thordarson, T., & Self, S. (1996). Sulfur, chlorine and fluorine degassing and atmospheric loading by the Roza eruption, Columbia River Basalt Group, Washington, USA. *Journal of Volcanology and Geothermal Research*, *74*, 49–73.

Thunell, R., Federman, A., Sparks, R. S. J., & Williams, D. (1979). The age, origin, and volcanological significance of the Y-5 ash layer in the Mediterranean. *Quaternary Research*, *12*(2), 241–253. https://doi.org/10.1016/0033-5894(79)90060-7

Ton-That, T., Singer, B., & Paterne, M. (2001). 40Ar/39 dating of latest Pleistocene (41 ka) marine tephra in the Mediterranean sea: Implications for global climate records. *Earth and Planetary Science Letters*, *184*(3–4), 645–658. https://doi.org/10.1016/S0012-821X(00)00358-7

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

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

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

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

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

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

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

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

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

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

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

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

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

Tables

	Volume calculations (km³)					
Authors	Plinian fallout	Co-plinian ash	PDC	Co-ignimbrite ash	Y-5	Total
Thunell et al., 1979			30-40*		30-40*	60-80*
Cornell et al., 1983					73	>150
Fisher et al., 1993			500			
Civetta et al., 1997	25*		120*			145*
Rosi et al., 1999	15					
Fedele et al., 2003						200*
Perrotta and Scarpati, 2003	4	16		100 (42*)		
Rolandi et al., 2003			180	140		320 (200*)
Giaccio, 2006	10 (3*)		385 (215*)	180 (86*)		575 (300*)
Marianelli et al., 2006	20*		130*			150*
Pyle et al., 2006				72-120 (31-50*)		105-210*
Pappalardo et al., 2008	20*		180*			200*
Costa et al., 2012				250-300 (104-125*)		430-680 (180-280*)
Scarpati et al., 2014			54 (25*)	100 (42*)		
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*)				

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

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

Table 2. *The values of thickness (m), area (km^2), volume (km^3), cumulative volume (km^3) and the percentage of volume for each isopach.*

	Bulk Volume (km^3)	DRE Volume (km^3)
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

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

Figures

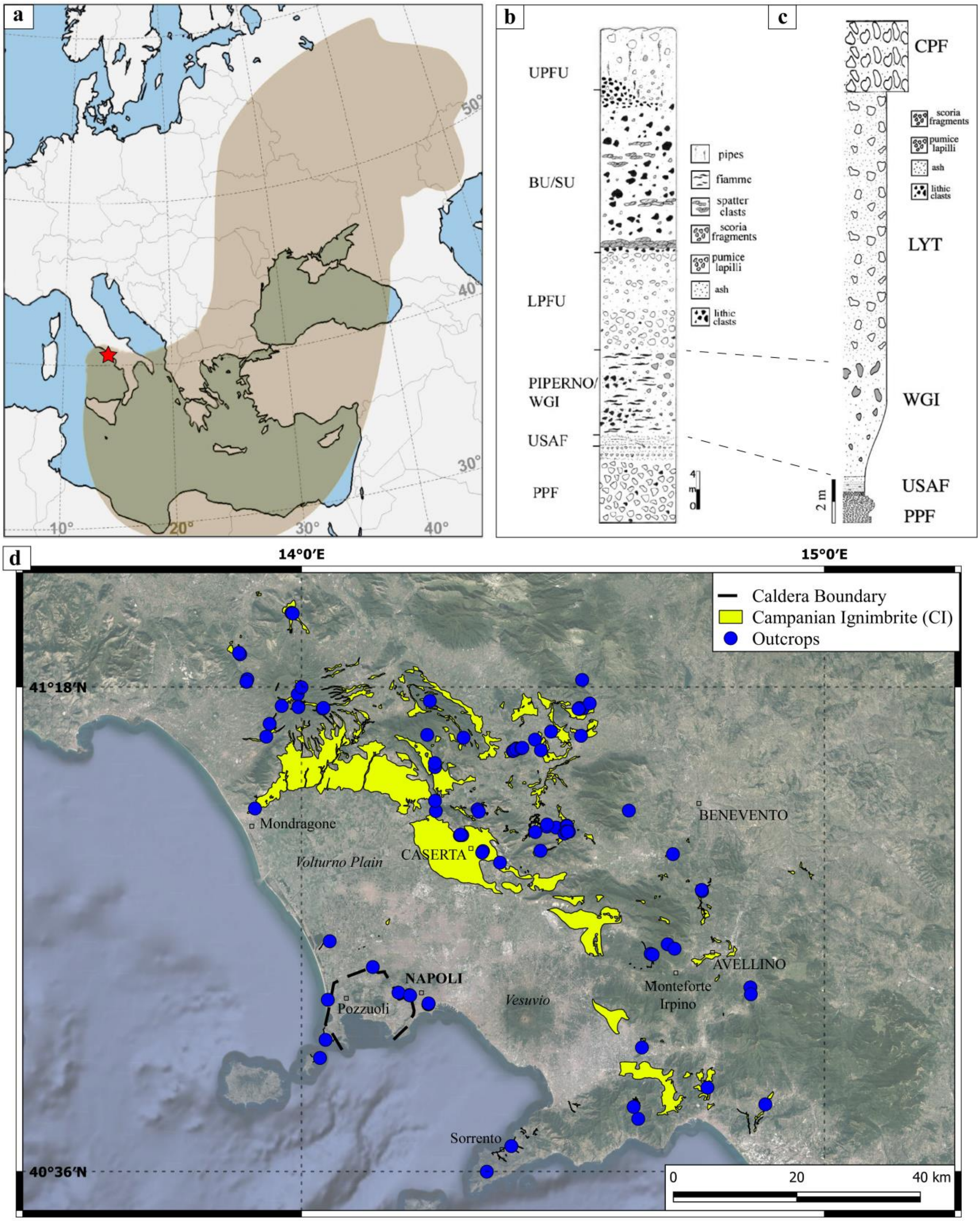


Figure 1. *The Campanian Ignimbrite distribution.* ***(a)*** *Dispersal area of the CI tephra from the Campi Flegrei caldera (red star), modified from Giaccio et al. (2017). Stratigraphic type-sections of CI proximal* ***(b)*** *and distal* ***(c)*** *deposits modified from Fedele et al. (2008) and Cappelletti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

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

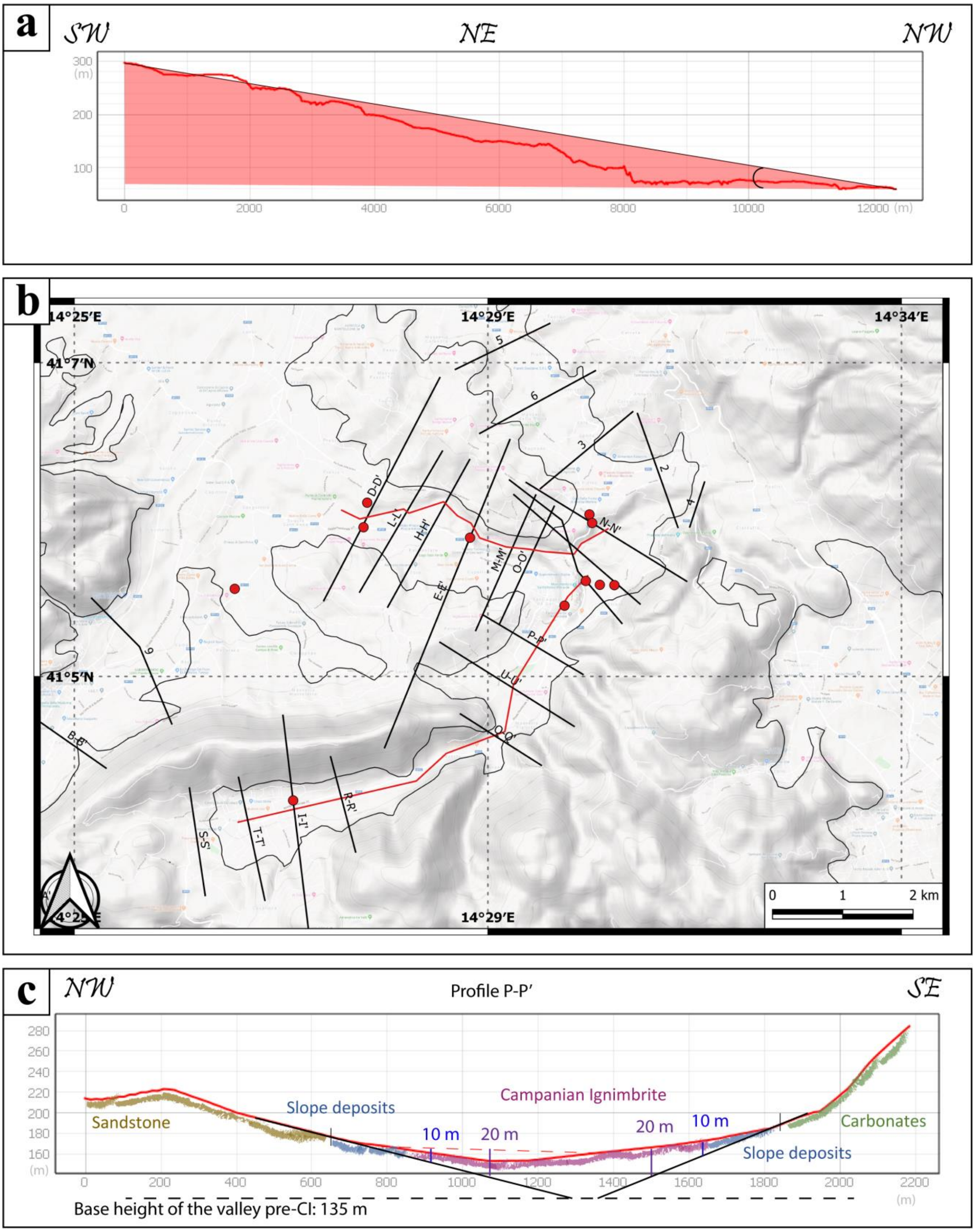


Figure 2. *The topography reconstruction in the Sant'Agata dei Goti area.* ***(a)*** *The modern valley is used as a reference for the paleo-slope during the CI eruption.* ***(b)*** *A series of profiles traced to study the paleo-valley; the red dots are outcrops where the CI is exposed.* ***(c)*** *Reconstruction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

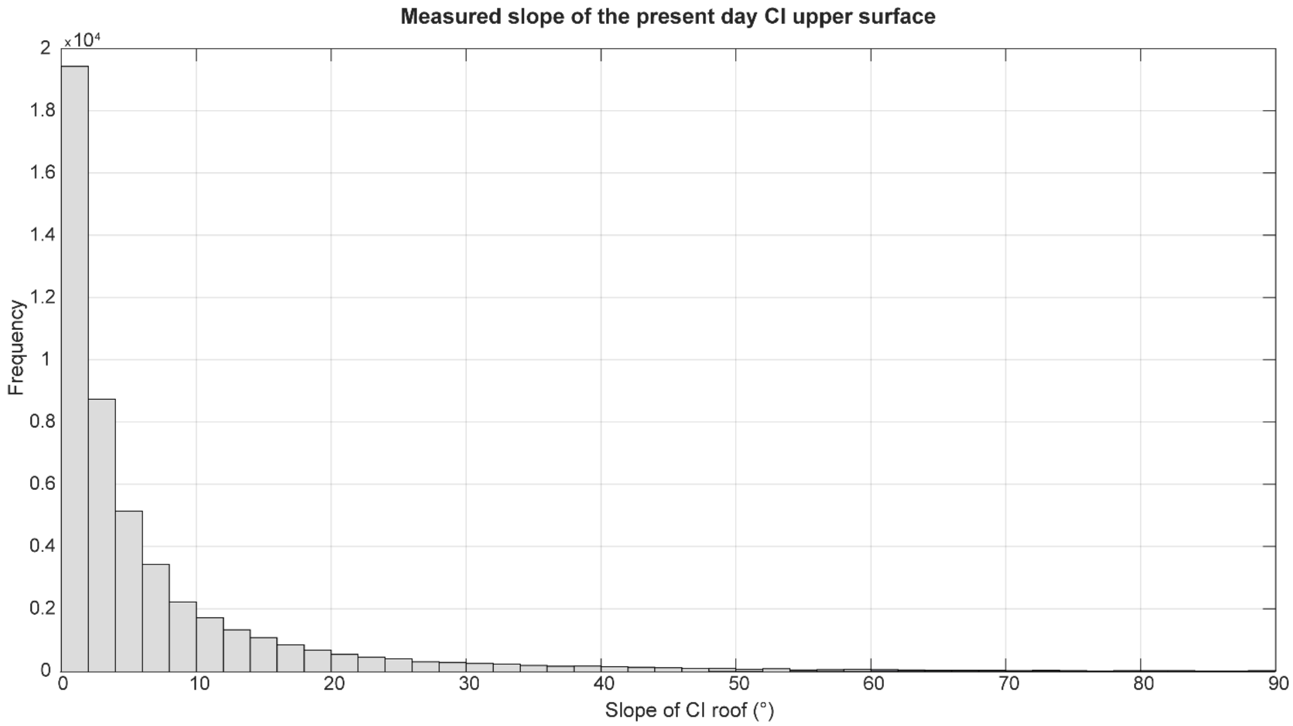


Figure 3. *Frequency of the slope of the upper surface of the CI. At least 80% of the exposed CI upper surface slopes less than 10°.*

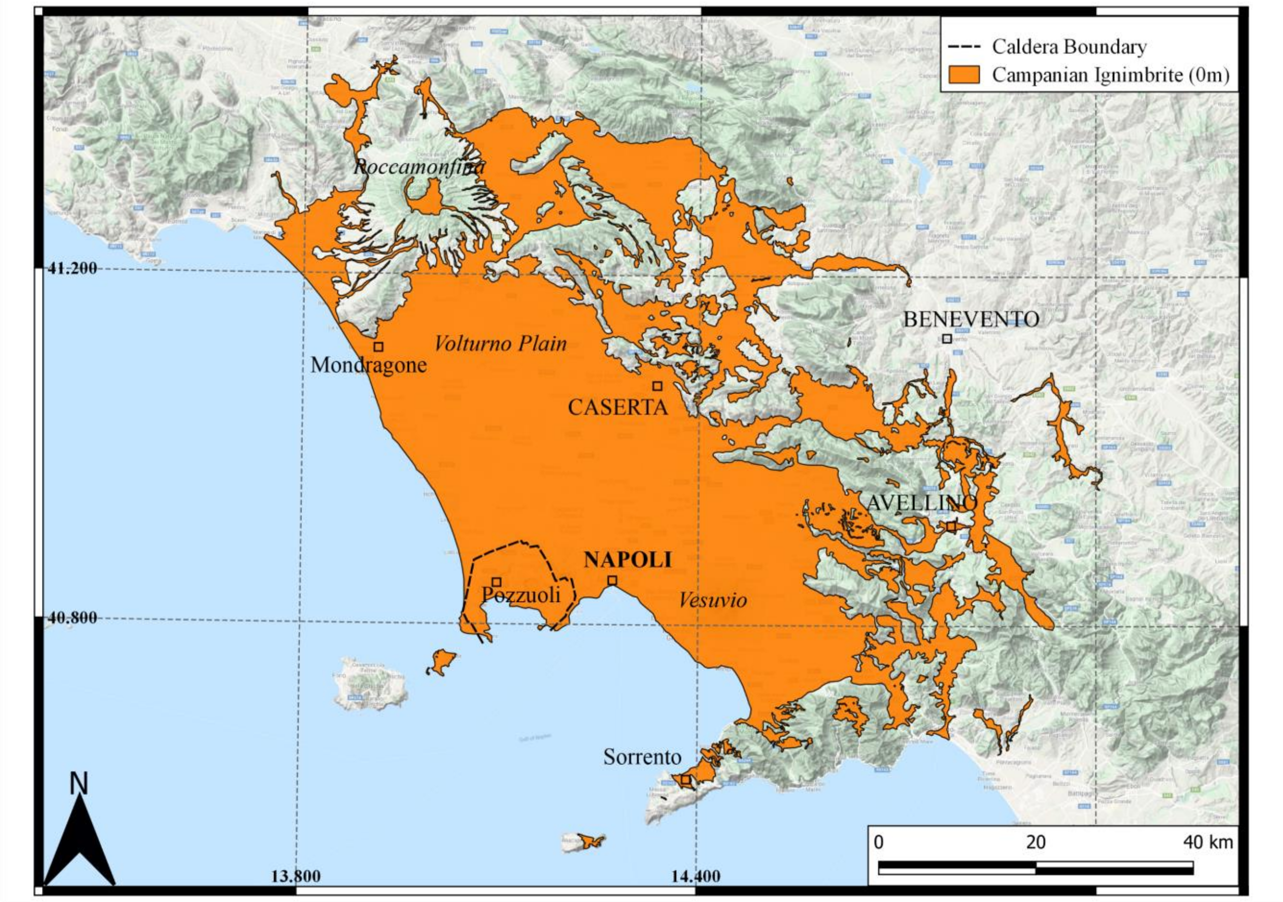


Figure 4. *The areal extent of the CI, enclosed within the isopach 0 m is shown in orange. The total area covered by the preserved deposits of CI is 3216 km*^{2}*, the envelopment with a shape is equal to 7547 km*^{2}*.*

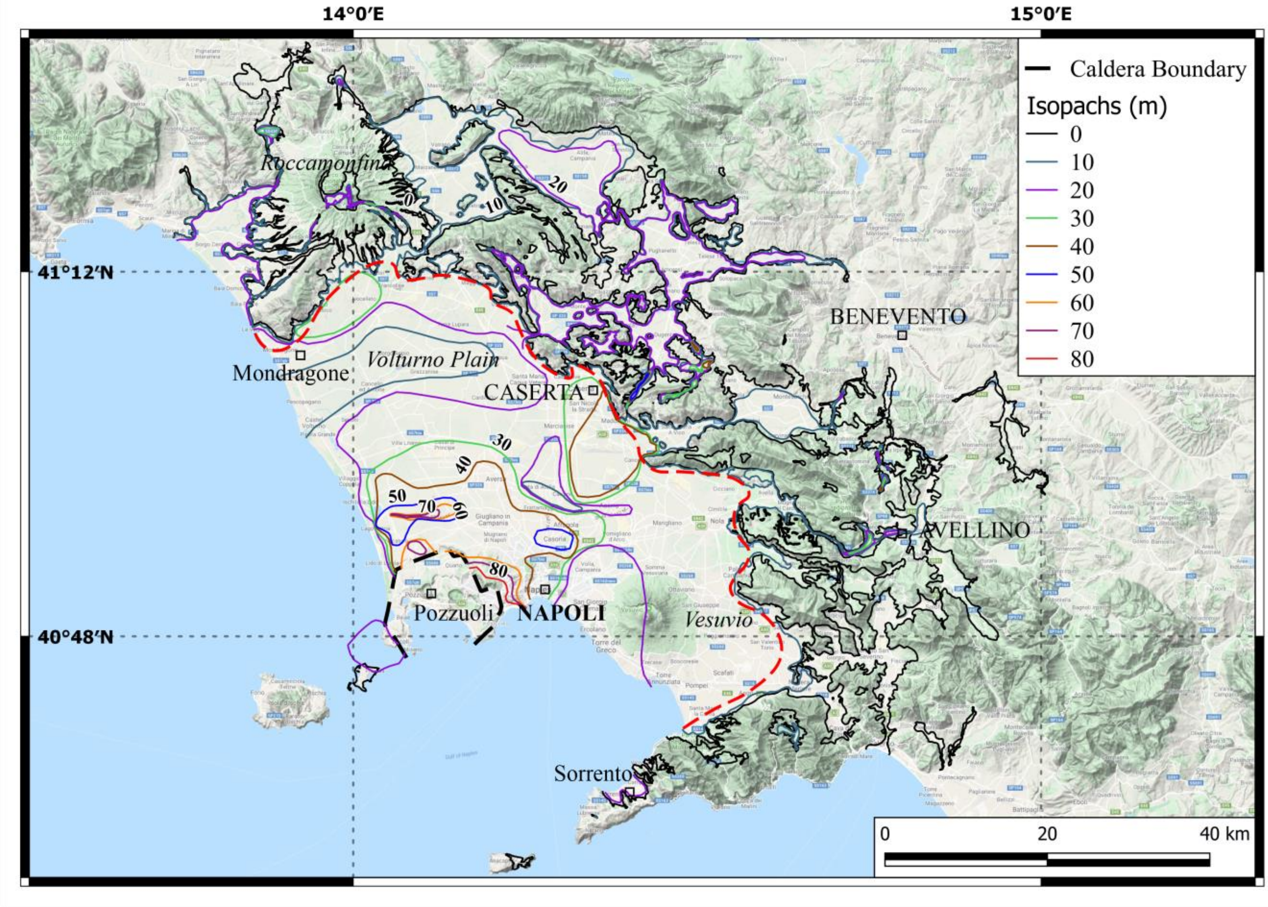
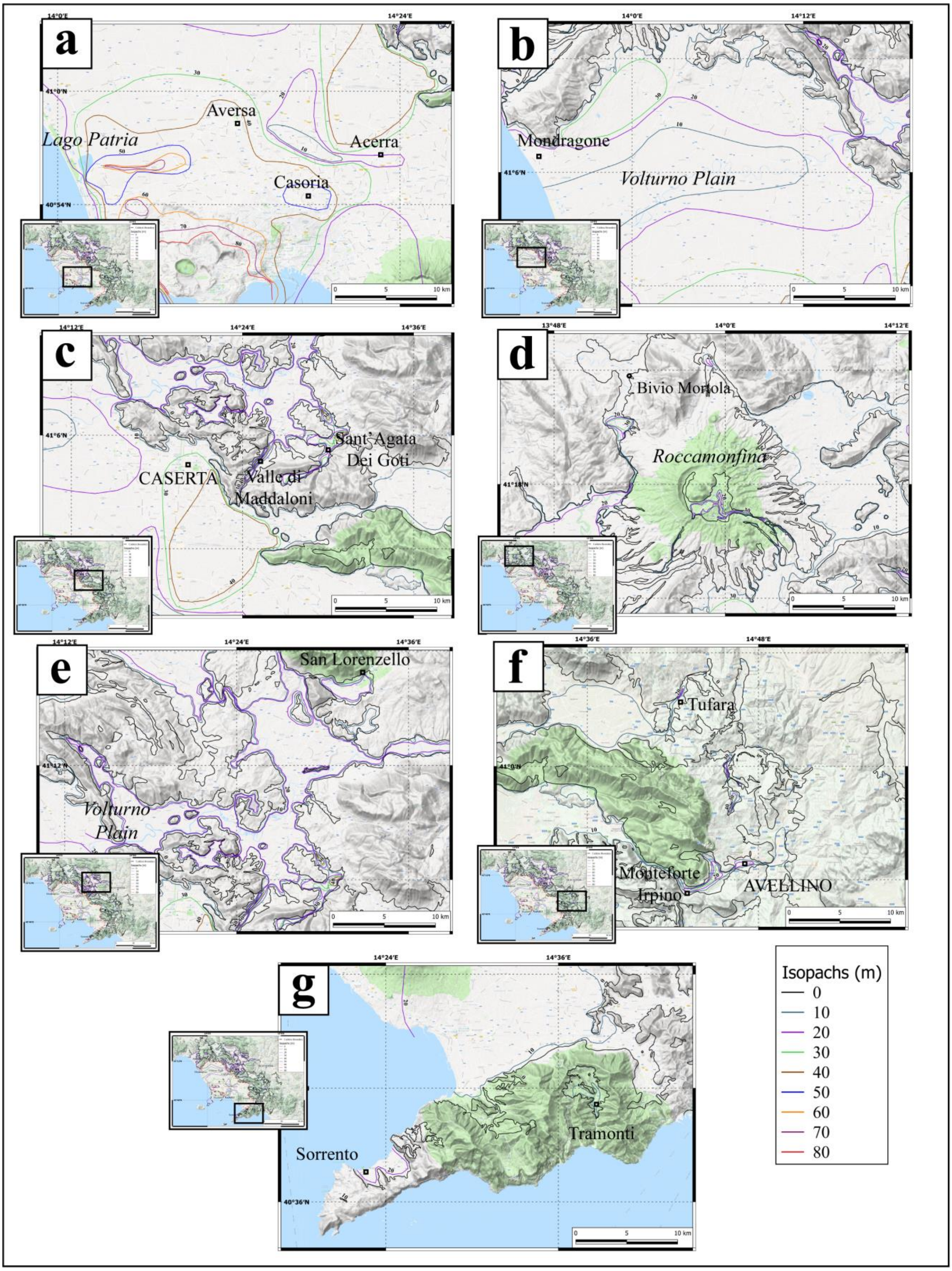


Figure 5. *Isopach map of the preserved extra-caldera deposits of the Campanian Ignimbrite. This map refers only to the pyroclastic density current deposits; it excludes the Plinian fallout and the co-ignimbrite ash. The different colors for each isopach are reported in the map key. The red dashed line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

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*

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

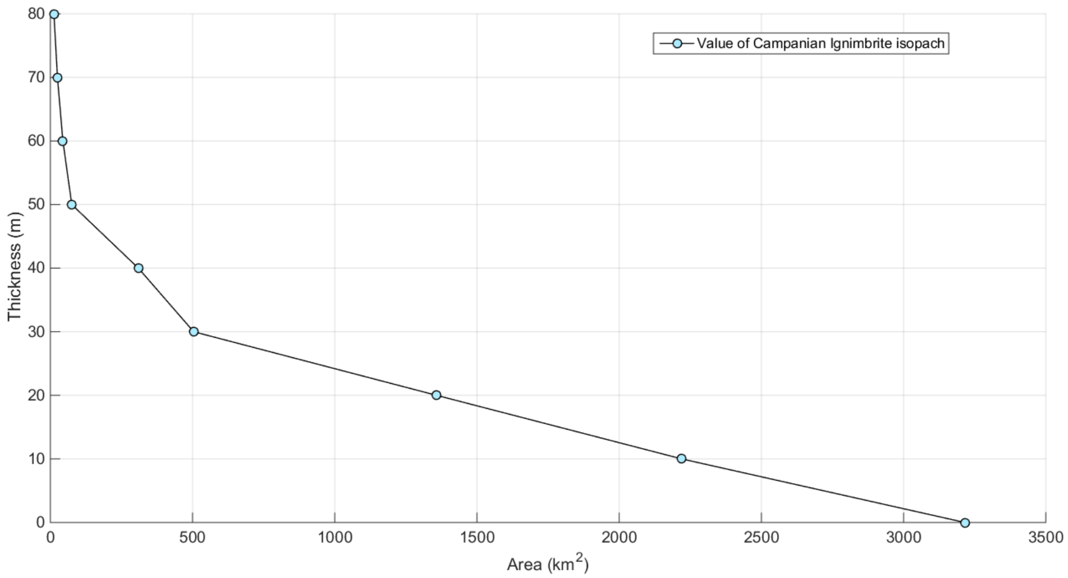


Figure 7. *The thickness (m) plotted against the area (km^2) of each isopach of the preserved deposits of the CI PDC. The volume is the subtended area of this plot.*

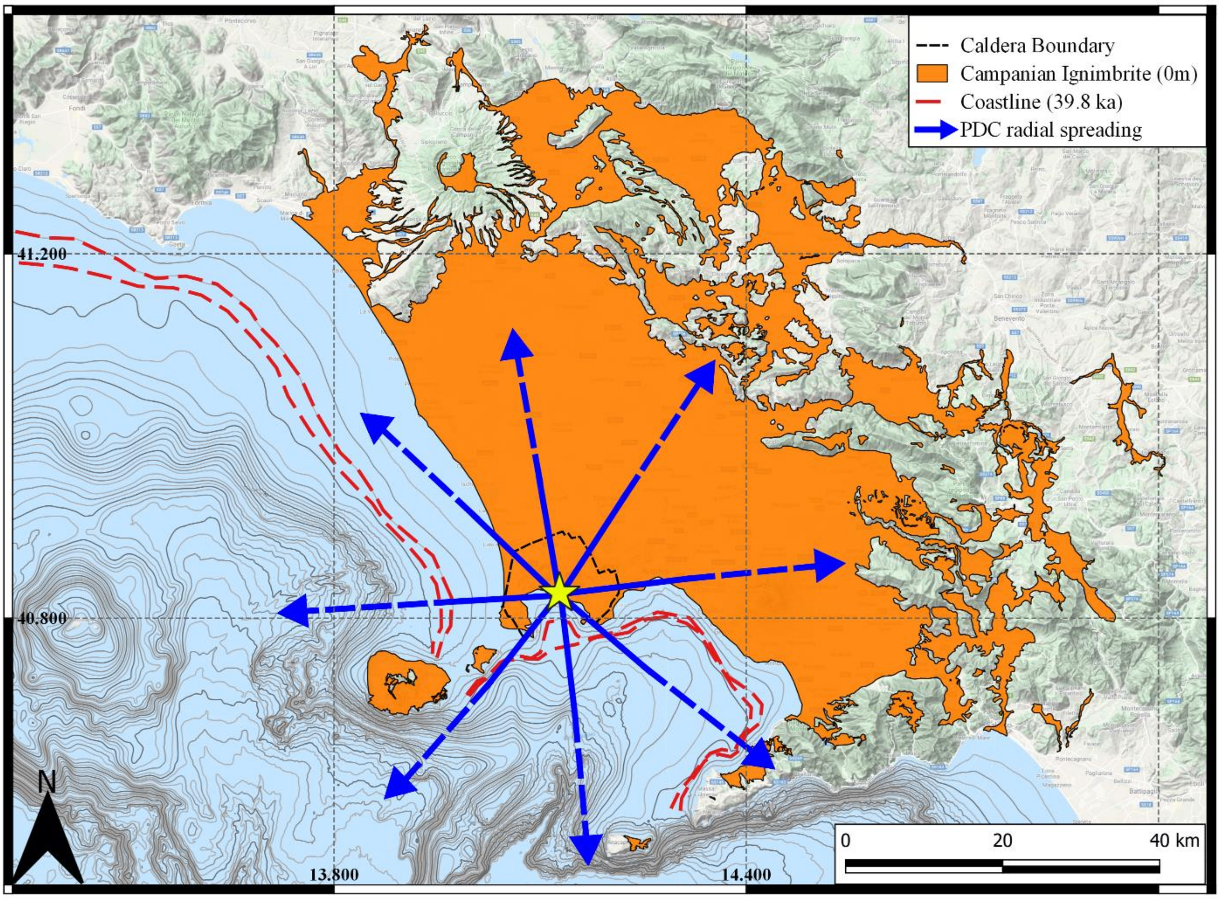


Figure 8. *Bathymetry of the submerged area of the Campi Flegrei Caldera. The red line is the 40 ka coastline, equivalent to -75 – -87 m of the present one. The blue arrows indicate the possible radial spreading of the PDC based on outcrops disposed radially from the center of the Caldera (yellow star)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