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Quantifying volcanic ash dispersal and impact of the Campanian Ignimbrite super-eruption

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[1] We apply a novel computational approach to assess, for the first time, volcanic ash dispersal during the Campanian Ignimbrite (Italy) super-eruption providing insights into eruption dynamics and the impact of this gigantic event. The method uses a 3D time-dependent computational ash dispersion model, a set of wind fields, and more than 100 thickness measurements of the CI tephra deposit. Results reveal that the CI eruption dispersed 250–300 km^3 of ash over ∼3.7 million km^2. The injection of such a large quantity of ash (and volatiles) into the atmosphere would have caused a volcanic winter during the Heinrich Event 4, the coldest and driest climatic episode of the Last Glacial period. Fluorine-bearing leachate from the volcanic ash and acid rain would have further affected food sources and severely impacted Late Middle-Early Upper Paleolithic groups in Southern and Eastern Europe. **Citation:** Costa, A., A. Folch, G. Macedonio, B. Giaccio, R. Isaia, and V. C. Smith (2012), Quantifying volcanic ash dispersal and impact of the Campanian Ignimbrite super-eruption, *Geophys. Res. Lett.*, *39*, L10310, doi:10.1029/2012GL051605.

1. Introduction

[2] The ∼39 ka Campanian Ignimbrite (CI) caldera-forming super-eruption is the largest volcanic eruption in Europe in the last 200 kyrs [*Fedele et al.*, 2003; *Sparks et al.*, 2005]. Enormous amounts of volcanic aerosols are injected into the stratosphere during these events, affecting regional and possibly global climate [*Fedele et al.*, 2007]. The widely dispersed ash fall deposit from this super-eruption provides geoscientists with important temporal and stratigraphic markers that are invaluable in correlating and establishing the chronology of archaeological and paleoclimate archives [*Pyle et al.*, 2006; *Giaccio et al.*, 2008]. However, the ultimate distribution of the tephra deposit and therefore, erupted volume estimations [*Pyle et al.*, 2006; *Fedele et al.*, 2008] remain poorly constrained, therefore the impacts of the eruption on a continental scale could not be assessed. Here we use a novel method to quantify and reproduce the CI tephra deposit, applying a computational ash dispersion model combined with the analysis of a set of wind fields, and more than 100 thickness measurements of the CI tephra deposit.

[3] Modelling distal dispersal of tephra fallout from the most explosive eruptions on Earth is very challenging. Dispersal models are the only way to accurately constrain the volume of material ejected and gain further insight into plume dynamics during these gigantic events. Previous models typically considered a homogeneous wind profile derived from best fitting deposit measurements, but this simplification is inadequate to determine ash dispersal in distal regions, especially in presence of complex wind patterns. Winds largely control dispersal, but the ash driven into the atmosphere is so widespread that the meteorological conditions over the entire area for the whole duration of the eruption need to be considered, and this is not available for past eruptions. Moreover, accurate estimation of tephra volumes from deposit thinning in very distal regions is almost impossible, as isopachs cannot be constructed because outcrops are too scarce [*Rose and Durant*, 2009]. For these reasons, tephra volume estimates for large eruptions, and especially super-eruptions are poorly constrained [*Self*, 2006]. Most of the material erupted during the CI eruption was deposited by pyroclastic density currents [*Fisher et al.*, 1993], and thus co-ignimbrite ash is likely to constitute proportion of the distal fallout. Previous estimates of the bulk-volume of the distal ash fallout range from 70 to 120 km^3, obtained from deposit thinning [*Pyle et al.*, 2006; *Perrotta and Scarpati*, 2003]. Constraining volume and dispersal has implications for volcanic hazards and eruption dynamics, and for paleoenvironmental research, as ash layers of these large eruptions are used to synchronize paleoclimate records [e.g., *Lowe*, 2011].

2. Computational Methodology and Input Data

[4] We use a new method to determine the CI tephra dispersal through to the ultra-distal regions (up to ∼2500 km from the volcano), and assess the volume of this widespread tephra deposit. A set of fully 3D time-dependent meteorological fields across the region, and a range of volcanological input parameters (erupted mass, mass eruption rate, column height, and total grain size distribution) were used in several hundreds of simulations of the FALL3D ash dispersal model [*Costa et al.*, 2006; *Folch et al.*, 2010]. Optimal values were obtained by best fitting measured CI deposit thicknesses over the entire dispersal area (113 locations, see Table S1 in the auxiliary material) and minimizing

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Table 1. Best Fit Results of Tephra Dispersal Inversion for the CI Super-eruption

Modelled Dispersion Parameters	Explored Range	CI-173R[a]	CI-330[a]
Tephra volume (kg)	Calculated	2.5×10^{14}	3.0×10^{14}
Tephra volume (km^3)	Calculated	250	300
Duration (days)	1–5	4.5	2
Mass eruption rate of ash fallout only (kg/s)	10^7–10^{10}	6.4×10^8	1.7×10^9
TGSD-maxima μ_1/μ_2 (in Φ-unit)[b]	0–3/6–9	6.5/2.0	6.5/2.0
TGSD-variances σ_1/σ_2 (in Φ-unit)[b]	1–3/1–3	2.0/2.0	2.0/2.0
Column height (km)	20–50	37.5	40
Suzuki coefficient (–)[c]	2–9	9	9
Density of aggregates (kg/m^3)[d]	100–600	300	300
Diameter of aggregates (μm)[d]	Assumed	200	200
Average deposit density (kg m^{-3})	Assumed	1000	1000
Correlation coefficient[e]	Calculated	0.77	0.72
T-Test[e]	Calculated	0.65	0.98
Δ^2-value[e]	Calculated	0.11	0.16

[a]These scenarios are the combination of meteorological fields and volcanological parameters that best reproduce the observed deposits. CI-173R corresponds to the meteorological synoptic fields from 5 to 12 December 1991 rotated 7° anti-clockwise around the vent; and CI-330 corresponds to the meteorological synoptic fields from 5 to 12 November 1995.

[b]Total grain-size distribution (TGSD) is assumed to be bi-Gaussian, with maxima at μ_1 and μ_2 and corresponding variances σ_1 and σ_2; particle diameters d are expressed in Φ-unit where d(mm) $=2^{-\Phi}$.

[c]The eruption source is described in a purely empirical way in order to reproduce the optimal geometrical shape of the deposits using the Suzuki distribution [*Suzuki*, 1983; *Pfeiffer et al.*, 2005]. In this the eruption column acts as a vertical line source (simplification only valid in distal areas). All thickness measurements <50 km from the vent were excluded.

[d]Determined using an aggregation model similar to that of *Cornell et al.* [1983].

[e]Relative mean square error based on the differences between log(measured thickness) and log(simulated thickness).

the deviation of regression, as in *Folch et al.* [2010].[1] This computationally intensive methodology allowed us to reconstruct the volume and tephra dispersal from the CI super-eruption, and constrain key eruption parameters.

[5] A set of five hundred synoptic meteorological fields was generated using 15 years of European Centre for Medium-Range Weather Forecasts (ECMWF), ERA-40 reanalysis obtained from the data server (http://www.ecmwf.int/reasearch/era/do/get/era-interim). The ERA-40 reanalysis archive contains data in six-hour intervals and at 23 pressure levels, ranging from 1000 to 1 hPa, and at a 2.5° horizontal resolution. Our methodology assumes that this collection of modern winds fields can statistically represent those at the time of the CI eruption (~39 kyrs BP). Meteorological fields were interpolated to the FALL3D computational mesh with a 3 hour interval using a linear temporal interpolation, and a bilinear spatial interpolation.

[6] The distribution of mass within the column was calculated using an empirical parameterization [*Suzuki*, 1983; *Pfeiffer et al.*, 2005]. In order to account for aggregation processes (influencing fine ash dispersal), an aggregation model similar to that of *Cornell et al.* [1983] was used. The aggregation model assumes that 50% of the 63–44 μm ash, 75% of the 44–31 μm ash, and 95% of the less than 31 μm ash fell as aggregated particles with a diameter of 200 μm. More sophisticated aggregation models [e.g., *Costa et al.*, 2010] could not be employed to solve this kind of inverse problem as they are too computationally intensive.

3. Results

[7] The volcanological and meteorological parameters that best fit the observed deposits (thickness measurements in Table S1 in the auxiliary material) are reported in Table 1.

[8] The best fit results from the model indicate that the column height was ~37–40 km, the mass eruption rate associated with the ash fallout was $6.4 \times 10^8 - 1.7 \times 10^9$ kg/s, the effective ash-aggregate density was of 300 kg/m^3, and the eruption lasted 2–4 days. The total amount of fallout material deposited was $2.5 \times 10^{14} - 3.0 \times 10^{14}$ kg, which equates to 250–300 km^3 of tephra or 104–125 km^3 of magma (dense rock equivalent, DRE). Our calculated tephra fall volumes are 2–3 times larger than previous estimations [e.g., *Pyle et al.*, 2006; *Perrotta and Scarpati*, 2003]. Considering volume estimations of 180–380 km^3 for the proximal pyroclastic density current deposits [*Pyle et al.*, 2006], the total bulk volume of the CI eruption is 430–680 km^3 (180–280 km^3 DRE).

[9] The best-fit meteorological fields correspond to those that typically prevail in current autumn-winter periods (more detail provided in the auxiliary material).

[10] The correlation coefficient between log(measured thickness) and log(simulated thickness) is 0.77 (0.72 for the second best meteorological field), and the T-Test value is 0.65 (0.98 for the second best meteorological field). The modeled results are in general agreement with the measured thicknesses (i.e., most simulated thicknesses are between 1/5 and 5 times the observed thicknesses; see auxiliary material), the relative mean error, Δ, is approximately 0.3 log-units, which implies there is about a factor 2 error on the estimation of the mass, that is similar to typical uncertainties associated with classical techniques [*Bonadonna and Costa*, 2012].

[11] The eruption column height, duration, and total grain size distribution are consistent with those estimated by field and laboratory analyses [*Rosi et al.*, 1999]. Furthermore, the simulated grain-size at Kostenki, in the ultra-distal region, is similar to the measured values [*Pyle et al.*, 2006].

[12] The column shape parameter (mass distribution within the column) was also determined from the inversion, which gives a high Suzuki coefficient (A = 9). This high value is different from those characterizing a sustained Plinian column, which typically has $A \approx 4$ with the maximum of the mass distribution at ¾ of the column height

[1]Auxiliary materials are available in the HTML. doi:10.1029/2012GL051605.

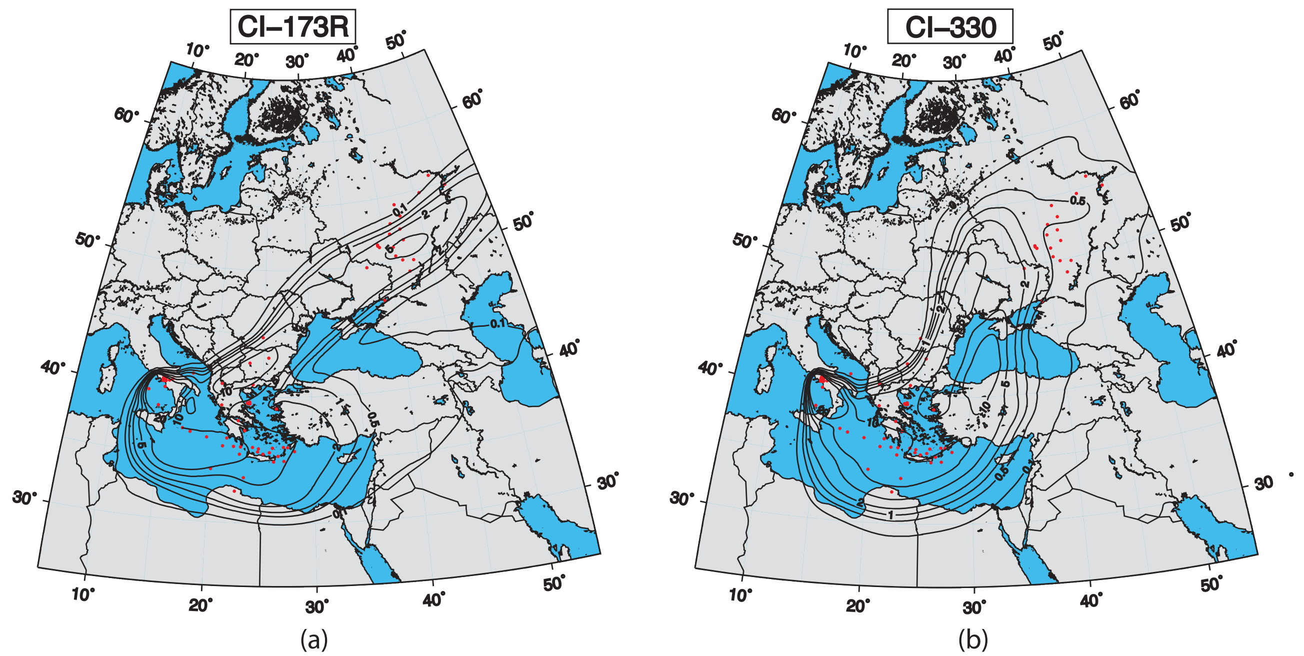

Figure 1. Isopach maps showing CI ash thickness (intervals 0.1, 0.5, 1, 2, 5, 10, 20 cm), as modeled using FALL3D. Red dots are points where the tephra thickness was measured (reported in Table S1 in the auxiliary material). The best fit simulations of the ash dispersal are displayed, (a) CI-173R and (b) CI-330 (see Table 1 for the parameters).

[*Pfeiffer et al.*, 2005; *Sparks*, 1986]. This may indicate that ash fallout was mainly from a co-ignimbrite cloud. The buoyant elutriated mixture of ash and volatiles rising off the pyroclastic flows would have formed the co-ignimbrite column, which would have been displaced from the vent [*Woods and Wohletz*, 1991]. The actual shape and extent of the fallout source is not relevant to the model as only the deposits >50 km the vent were considered.

[13] The field evidence shows that the eruption started with a Plinian phase followed by large pyroclastic density currents [*Wulf et al.*, 2004] that scaled topographic highs more than 70 km from the vent [*Fisher et al.*, 1993]. The column collapse that generated the widespread ignimbrite was most likely due to an increase of the mass eruption rate [*Woods and Bower*, 1995]. The actual mass eruption rate (MER) for the ignimbrite phase must have been much larger than $\sim 10^9$ kg/s, the value we estimated to be associated to the fallout only (Table 1). As the eruption column was ∼37–40 km, the actual MER of the coignimbrite phase, in accord with the *Woods and Wohletz* [1991] model, must have been one order of magnitude larger, i.e., $\sim 10^{10}$ kg/s.

[14] The simulated best-fit deposits are shown in Figure 1 and for the first time there are estimates of the shape of the dispersal area and extent of the ultra-distal deposits.

4. Implications and Discussion

[15] Using the sulphur content of the total amount of CI magma erupted, derived from melt inclusions and matrix glass [up to 800 pm SO_3; *Signorelli et al.*, 2001], and the magma volumes from the model presented, the amount of SO_2 emitted during the CI eruption was calculated [after *Self et al.*, 2004] to be ∼450 Tg (∼200 Tg of this would have been released into the stratosphere). This amount is comparable to those of other super-eruptions, namely Toba and Bishop Tuff [*Scaillet et al.*, 2003]. Numerical simulations performed to study the climate response to large volcanic eruptions [*Timmreck et al.*, 2009] suggest that the hemispheric cooling induced by the volumes of CI aerosols would have been ∼1–2°C, and lasted 2–3 years. Even this short-term cooling would have been enough to cause severe ecosystem alteration [*Rampino*, 2002].

[16] Using the total magma volume and the melt composition [500–5500 ppm F; *Pappalardo et al.*, 2008] we estimated that 100–300 Tg of fluorine was originally dissolved in the melt, and that once the ash was deposited this fluorine would have leached out into the soil [*Cronin et al.*, 2003]. In addition, large amounts of chlorine and fluorine, along with sulphur dioxide, would have been ejected into the troposphere and may have produced intense acid rain in the area downwind of the volcano.

[17] Volcanic ash deposition would have affected ecosystems by chemical and physical changes in the water of lakes and rivers, acid rains, and by the partial or total destruction of forests and grasslands [*Delmelle*, 2003; *Kockum et al.*, 2006]. Consumption of the ash covered vegetation would have resulted in fluorosis [*Cronin et al.*, 2003] associated with fluorine leaching from the silicate glass, which damages eyes, teeth, bones and internal organs of ruminants and other herbivores, such as aurochs, bison, elk, mammoths and horses. Acid rains, water contamination, destruction of food sources and ash inhalation would have had a great impact on Early Upper Paleolithic communities in the region [*Fedele et al.*, 2008]. As most of the East Mediterranean area, Balkans, and part of Caucasus region were covered by more than 5 mm of ash (Figures 1 and 2) the ecosystems would have been greatly affected. The recovery of vegetation would have taken from one year up to decades (http://volcanoes.usgs.gov/ash/agric/index.html, and references therein).

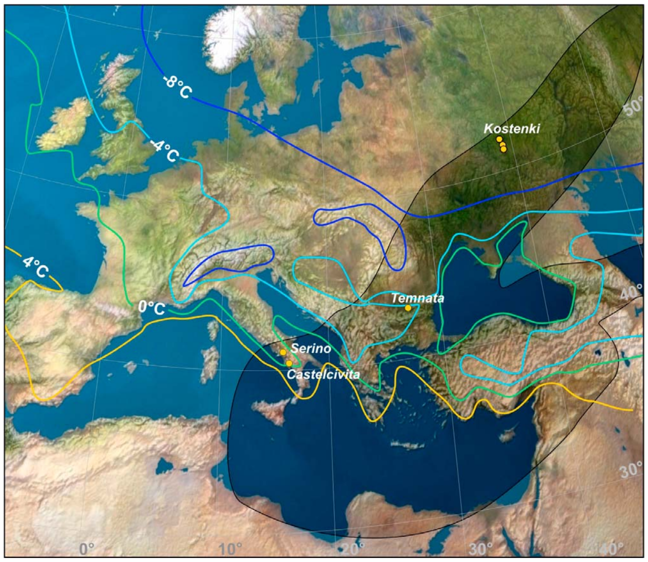

Figure 2. Distribution of the archeological sites containing CI tephra (yellow circles from *Fedele et al.* [2003] superimposed on a map showing the simulated mean winter temperature isolines in Europe during the relatively warm interstadial phase (∼40 ka) before the CI eruption (modified from *van Andel* [2002]). The 0.5 cm isopach of the simulation CI173R is also highlighted as a shaded area.

[18] The CI super-eruption occurred just after the onset of Heinrich Event 4, HE4 [*Fedele et al.*, 2003, 2008; *Müller et al.*, 2011], which is characterised by a very cold and dry climate. This change in Northern Hemisphere climate, combined with the volcanic winter, would have severely impacted Early Upper Paleolithic groups within Europe [*Fedele et al.*, 2003, 2008]. However, it is difficult to quantify the actual impact of the CI eruption on populations living in the region (for an extensive description of the HE4-CI combined event see *Fedele et al.* [2008]). Nevertheless, the eruption marks distinct bio-cultural changes in Western Eurasia, termed the Middle to Upper Palaeolithic transition. Archaeological sites covered by the CI ash (see Figure 2) often have clear post-eruption sterile layers indicating that occupation in the region changed, even at sites characterized by millennial-long continuous occupation [*Fedele et al.*, 2008; *Giaccio et al.*, 2008; *Pinhasi et al.*, 2011]. In addition, the youngest Neanderthal fossils in the Caucases region are older than ∼40–39 ka [*Pinhasi et al.*, 2011], allowing the possibility that combination of the eruption and HE4 led to a demographic crash in the region. Some Early Upper Palaeolithic lithic industries and fossil remains indicate that modern humans may also have been in the region prior to the eruption, but populations appear to have been limited [*Anikovich et al.*, 2007]. Once the large areas that would have been inhospitable for years had recovered they were colonised by modern humans, as marked by a fully developed Upper Palaeolithic culture. Our reassessment of the CI eruption parameters and dispersal provides support for theory that the combination of HE4 and the CI eruption drove ecological changes in European Late Pleistocene and affected biocultural processes [*Fedele et al.*, 2008; *Golovanova et al.*, 2010].

[19] In summary, the application of a novel computational method constrains the magnitude and ash dispersal of the CI super-eruption. The estimation of the key eruption parameters, such as volume, mass eruption rate, duration, column height, total grain-size distribution, and the tephra dispersal footprint have important implications for impact assessment of such catastrophic events. The CI eruption provides an ideal case study for assessing the widespread impact of large eruptions on climate, ecosystems and human populations. Results of this method agree well with the available observations of the ash dispersal, indicating that the model is robust. Since computational power is ever increasing, this may become a standard method to constrain the main eruption parameters of past super-eruptions, which are key to understanding eruption dynamics, and the impacts of these kinds of events.

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