Mineralogy and Petrology (2003) 79: 67–78
DOI 10.1007/s00710-003-0002-8

Mineralogy
and Petrology

Volume partition between the plinian and co-ignimbrite air fall deposits of the Campanian Ignimbrite eruption

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Received March 3, 2002; revised version accepted June 4, 2003
Editorial handling: R. Scandone

Summary

Large-scale volcanic plumes, either generated by discharge of material directly from a vent or developed from the top of pyroclastic flows, produce laterally spreading umbrella-shaped clouds that disperse pyroclastic material over large areas. During plinian eruptions followed by pyroclastic flows, an enormous quantity of ash particles produced both by sustained plumes and by the buoyant portion of pyroclastic flows settle far from the source and form widespread fall deposits. To fully evaluate the magnitude of the plinian phase for this kind of eruptions is fundamental for distinguishing between the different sources of fine ash. In this paper we demonstrate that the plinian and ignimbrite contribution to the distal ash fall can be discriminated based on thickness versus distance relationships. The Campanian Ignimbrite eruption (CI; 39,000 yr B.P.) in southern Italy, provides an important case study. This was a huge ignimbrite-forming explosive event preceded by a plinian outburst. We present a new distribution of the thick, stratified pumice fall deposit formed immediately before the emplacement of the ignimbrite and reconstruct the distribution of the CI-correlated tephra fall dispersed in eastern Europe and in the eastern Mediterranean Sea over an area exceeding $3 \times 10^6\,km^2$. The volumes calculated for the proximal plinian, co-plinian and co-ignimbrite deposits of the CI eruption are respectively: $4\,km^3$, $16\,km^3$ and almost $100\,km^3$.

Introduction

The volume (magnitude) of plinian fall deposits is a widely used parameter to characterise the size of the corresponding eruptive event (*Walker*, 1980). Volume also represents a key-parameter in the definition of the volcanic explosivity index (VEI), a semi-quantitative indicator that proved to be extremely useful in comparing the size of different explosive eruptions (*Newhall* and *Self*, 1982).

Tephra fall volume evaluations are currently carried out by mapping the thickness of the pyroclastic fall deposits and integrating the resulting isopachs on log-thickness versus $A^{1/2}$ diagrams (*Pyle*, 1989; *Fierstein* and *Nathenson*, 1992). This approach is based on the assumption, derived from several field observations, that tephra fall deposits thin exponentially away from the eruptive vent: it is thus possible to extrapolate the trend of the thickness observed in proximal areas over longer distances and to calculate the total volume of the deposit studied. However, recent studies (*Hildreth* and *Drake*, 1992; *Fierstein* and *Hildreth*, 1992) documented that the thickness decrease of tephra fall deposits away from the vent can be actually more complex than commonly assumed. The thinning out of the deposit is described by at least two straight-line segments with a well defined break in slope. These features were interpreted by *Bonadonna* et al. (1998) as due to changes in the particle settling behaviour during the lateral expansion of the eruptive cloud. In such cases it becomes difficult to correctly trace the thickness variations from proximal to very distal areas: major problems arise as a consequence of the limitation on the amount of field data available, especially in the distal areas where the ash layers are thin and easily disturbed or eroded. Consequently, a simple extrapolation of the proximal data to the distal regions can lead to a significant underestimation of deposit volume. Furthermore, plinian eruptions are often associated with the emplacement of large-volume pyroclastic flows that generate a co-ignimbrite plume (*Woods* and *Wohletz*, 1991; *Woods*, 1998) rising buoyantly into the atmosphere and transporting ash particles over a very long distance. Consequently, the fine particles accumulated in distal areas may have two different sources: the expanding cloud related to the sustained eruptive column *and* the co-ignimbite plume. Inaccurate definition of the contribution of co-ignimbrite ash to the total tephra thickness in distal areas, leads to overestimation of the volume of the plinian deposit. Hence, in order to correctly evaluate the magnitude of each eruptive phase during explosive eruptions (e.g. plinian fallout), it is fundamental to discriminate among the different kinds of volcanic products and properly evaluate their respective volumes.

In this paper we present a new isopach map of the proximal distribution of the basal fallout products emplaced during the Campanian Ignimbrite (CI) eruption at 39,000 yr B.P. in the Campanian region (*De Vivo* et al., 2001). The map shows a distribution that differs significantly from that previously proposed (*Rosi* et al., 1999) and is drawn utilising a larger number of sections than those utilised in the previous study. Furthermore, we reconstruct, from different sets of previously published data (for references see below), the distribution of a widespread ash fall deposit correlated to the CI eruption and covering a large region from the eastern Mediterranean Sea to Russia. We use our mainland isopach map in conjunction with the distal distribution in order to evaluate the total volume of the fall products emplaced during both the plinian phase and the following ignimbrite phase. In this way, it was also possible to quantitatively assess the contribution of the fine-grained plinian ash (co-plinian in the sense of *Fierstein* and *Hildreth*, 1992) and co-ignimbrite products to the formation of the distal ash fall tephra.

The Campanian Ignimbrite eruption: volcanological background and source problem

The CI eruption was a large ignimbrite-forming eruption beginning with a plinian phase. The eruption occurred in the Campanian region (southern Italy) and represents the major explosive event in the Late Quaternary in the Mediterranean region (*Barberi* et al., 1978). The age of this eruption is a matter of debate: the ages obtained by ^{14}C datings on paleosols range from 17 Ka to 42 Ka (*Alessio* et al., 1973, 1976; *Scandone* et al., 1991; *Lirer* et al., 1991); while recent $^{39}Ar/^{40}Ar$ datings yield ages of about 36 Ka (*Deino* et al., 1992) and 39 ka (*De Vivo* et al., 2001).

The Campanian Ignimbrite is a pyroclastic flow deposit consisting of a grey welded trachytic tuff; locally its colour is yellow due to zeolitization (*Cappelletti* et al., this issue). The parental pyroclastic flow moved over 1000 m high mountain ridges and covered an area $>30{,}000\,km^2$. *Fisher* et al. (1993) suggested that the Campanian Ignimbrite progressively aggraded from the base of a pyroclastic current that moved across the landscape as an expanded and turbulent flow and deposited down valleys along paths dictated by slope direction.

In few outcrops, some authors (*Orsi* and *Rosi*, 1991; *Scandone* et al., 1991) identified a pumice fall layer directly at the base of the CI. Recently, two different units have been identified to form this fall deposit and a reconstruction of the eruptive dynamics has been proposed by *Rosi* et al. (1999).

The source area of the CI eruption is controversial. Campi Flegrei was considered the source area of this eruption by *Rittmann* (1950), *Rosi* et al. (1983), *Rosi* and *Sbrana* (1987) and *Barberi* et al. (1991) on the basis of some breccia deposits outcropping along the border of this volcanic field and interpreted as the proximal facies of the main ignimbrite. Other authors (*Di Girolamo*, 1970; *Barberi* et al., 1978; *Di Girolamo* et al., 1984; *Lirer* et al., 1987) proposed that the CI was fed through a fracture located a few kilometres north of Campi Flegrei. *Scandone* et al. (1991) suggested that a large structural depression located in the central Campanian Plain (Acerra depression) may have been enlarged after the eruption of the CI. Recently, a numerical simulation applied to the CI indicates a possible area of emission located northeast of Napoli (*Rossano* et al., 1996). Finally, *De Vivo* et al. (2001) who recognize different ignimbrite events in the Campanian Plain (dated between 205 and 18 Ka) claim that such events, among which the CI eruption could be related to fissures activated along neotectonic Appennine faults.

There is limited volcanological evidence to define the source area of the early, plinian phase of the CI eruption. Nevertheless, the lack of a proximal plinian fall deposit in the Campi Flegrei caldera associated with the coarse and welded facies possibly related to the main ignimbrite, together with new dispersal data (see the isopach map below) seems to indicate a possible source area east of Campi Flegrei.

Campanian plinian pumice fall deposit: stratigraphy and dispersal

The study area for the CI pumice fall deposit is a wide region extending from Roccamonfina volcano at the North, to Benevento at the East to the Sele Plain at

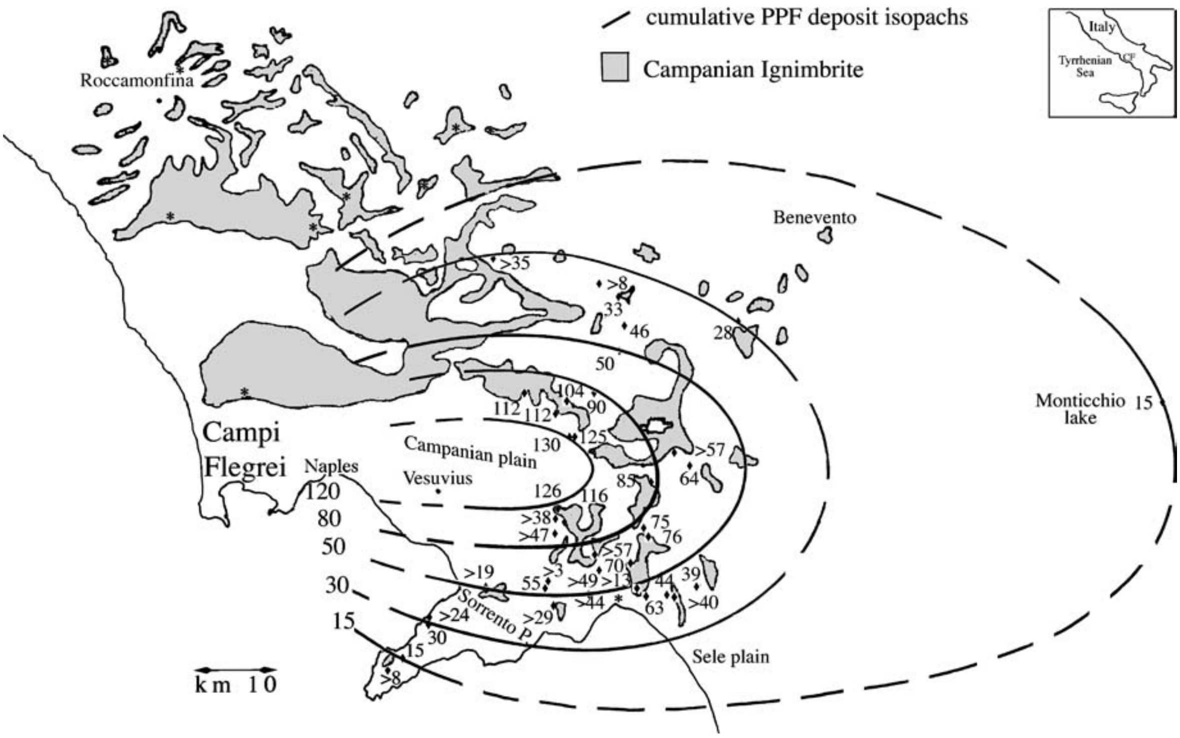

Fig. 1. Isopach map of the whole plinian fall deposit related to the Campanian Ignimbrite eruption. Cumulative thickness (in centimetres) of the fall deposit, for each studied site, is also shown. Asterisks indicate locations where the CI lies directly on the paleosol (i.e. thickness of the fallout deposit is zero). Proximal distribution of the Campanian Ignimbrite (after *Barberi* et al., 1978) is also shown

the South (Fig. 1). The number of sections where the plinian fall deposit is exposed is 38, while the sections where the CI rests directly on a paleosol is 11. At these latter localities the basal plinian fall deposit is missing because it was eroded by the overlying ignimbrite or because the sections are located outside the former depositional area. The location of the fall deposit outcrops is restricted to a 40×60 km sector at the eastern and southern parts of the Campanian Plain (Fig. 1). This distribution is due to: a) the original eastward dispersal of the plinian products; b) the burying of the first erupted airfall products under tens of metres of ignimbrite in the Campanian Plain; and c) the erosion of the loose, plinian deposit on the mountains bordering the Campanian Plain except where the thick and sintered ignimbrite has preserved the underlying fall deposit from erosion. The whole deposit is divided into different units (layers) on the basis of grain size, component variations, and graded bedding (Fig. 2). It consists of four main layers, A to D from the base to the top, made up by fine to coarse pumice lapilli with minor amounts of lithic clasts and crystals, except for the sandy layer C which shows a marked enrichment in lithic clasts and crystals. Pumice clasts are light grey in colour, well vesiculated and show aphyric to slightly porphyritic textures. This sequence is capped by a thin, stratified sandy to fine lapilli layer in the upper most part (E); it is frequently eroded and directly underlying the ignimbritic succession. Detailed

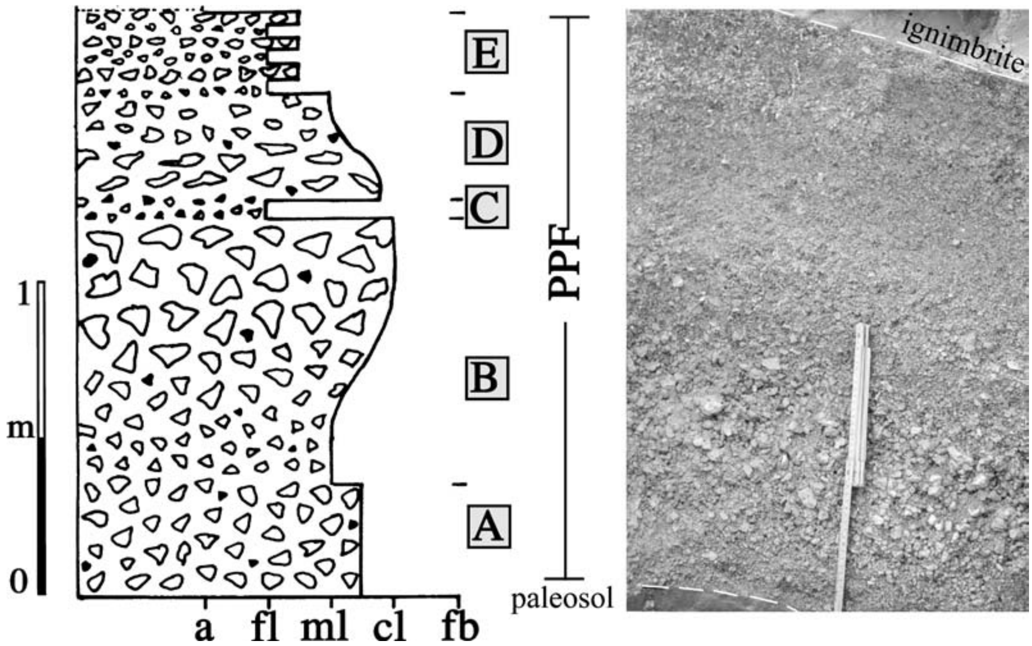

Fig. 2. Composite section of the plinian pumice fall deposit (PPF). The sketch shows name, maximum thickness, types of components (pumice: white; lithics, black) and grading styles of the five stratigraphical units into which the deposit has been divided. Maximum clasts size (mm): a (ash), f (fine lapillus), ml (medium lapillus), cl (coarse lapillus) and fb (fine block). On the right, photo showing typical vertical grain-size variation of PPF

data for individual units within the fall deposit are not relevant for this study and will be presented elsewhere.

From field data a total isopach map has been constructed (Fig. 1). Elongation of the isopach indicates that the dominant winds at the time of the eruption came from the West. This trend is consistent with the dispersal of most of Campi Flegrei and Somma-Vesuvius plinian fall deposits because of the prevalence of westerly winds in this region (*Rosi* and *Sbrana*, 1987; *Santacroce*, 1987). Downwind and crosswind extension as reconstructed from the 15 cm isopach is 100 and 65 km, respectively.

Dispersal of the distal ash fall tephra and comparison of proximal and distal grain size distribution

Plinian eruptions form widespread sheet-like pumice and ash fall deposits dispersed over thousands of square kilometres. The thin distal layers represent a large part of the erupted material, but an estimate of their total volume is often prevented by the rapid erosion of this fine-grained fallout material. Many studies have focused on the widespread tephra layer associated with the products of the CI eruption (*Thunnel* et al., 1979; *Sparks* and Huang, 1980; *Cornell* et al., 1983; *Melekestsev* et al., 1988; *Paterne* et al., 1988; *Cramp* et al., 1989; *Vezzoli*, 1991; *Seymour* and *Christanis*, 1995; *Narcisi* and *Vezzoli*, 1999). Chemical analyses, age dating and clast morphology studies performed on samples from deep sea cores collected in the Ionian and Aegean Seas (*Thunnel* et al., 1979; *Sparks* and *Huang*, 1980; *Cornell* et al., 1983; *Cramp* et al., 1989; *Vezzoli*, 1991) Tyrrhenian Sea (*Paterne* et al., 1988), Adriatic Sea (*Paterne* et al., 1988; *Calanchi* et al., 1998), in Greece (Peloponese Peninsula, *Vitaliano* et al., 1981; Kalodiki on the west coast and Philippi in the north-east, *Seymour* and *Christanis*, 1995), Bulgaria (*Harkovska* et al., 1990) Rumania, Ukraine and several places in Russia (*Melekestsev* et al., 1988) strongly support the correlation of the tephra to the CI eruption. Furthermore, a buried soil cropping out in the mainland of central Italy has been tentatively correlated with the airfall products of the CI eruption (*Frezzotti* and *Narcisi*, 1996). An incomplete isopach map of this ash deposit (named Y-5 in the Mediterranean Sea) was presented by *Cornell* et al. (1983) on the basis of thickness data from marine sedimentary successions in the eastern Mediterranean Sea.

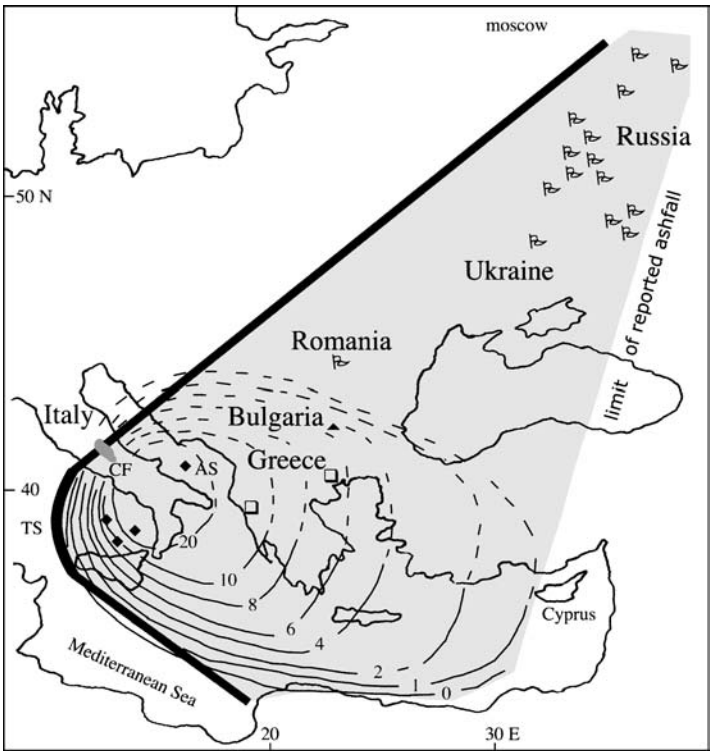

Fig. 3. Distribution of distal ash fall tephra associated with the Campanian Ignimbrite eruption. Note that the eastern trend of the dispersion is compatible with the trend of the proximal plinian fall products shown in Fig. 1. Isopachs on the Mediterranean Sea are redrawn from *Cornell* et al. (1983). Locations of this tephra layer are indicated by: flags in eastern Europe (*Melekestsev* et al., 1988), a triangle in Bulgaria (*Harkovska* et al., 1990), squares in Greece (*Seymour* and *Christanis*, 1995). Grey area in central Italy (redrawn from *Narcisi* and *Vezzoli*, 1999) is the distribution of a paleosol related with the CI fall deposit (*Frezzotti* and *Narcisi*, 1996). Diamonds indicate Tyrrhenian and Adriatic coring locations (*Paterne* et al., 1988). *CF* Campi Flegrei; *AS* Adriatic Sea; *TS* Tyrrhenian Sea

Using data from all previously cited sources, we present a new map showing a more complete view of the distal dispersal of this ash fall deposit (Fig. 3). The covered area is larger than $3 \times 10^6\,km^2$, extending from the eastern Mediterranean Sea to Russia. The direction of the dispersal axis inferred by this distribution is towards the east, widely coincident with that reconstructed for the proximal parts (compare with Fig. 1).

The airfall products of the CI eruption represent a rare example of a well preserved, prehistoric deposit thus allowing grain size analyses of samples from proximal as well as distal locations. Previous workers (*Sparks* and *Huang*, 1980; *Cornell* et al., 1983) have recognised that the Y-5 tephra is composed of two distinct layers at some sites close to Italy: a coarse lower unit and a finer, normally-graded upper unit with a sharp boundary in between. In most cores the Y-5 layer has a pronounced bimodal grain-size distribution which is interpreted as due to mixing of the fine and coarse units (*Thunnel* et al., 1979; *Sparks* and *Huang*, 1980; *Cornell* et al., 1983). These authors proposed that a plinian eruption column supplied the coarser particles and an ash cloud rising from a pyroclastic flow the finer ones.

In the following we compare published grain size data for the distal Y-5 layer with those which we obtained for the proximal area. Median size data (Md_ϕ) are plotted against distance from the source in Fig. 4. Both the median diameter of the proximal samples and of the coarse mode of distal samples decrease systematically with distance from the source. In contrast, the fine mode shows little change in median diameter with distance from the source. It is noteworthy that Md_ϕ decreases generally at a rate of 1ϕ for each 20–25 km distance in the Campanian region (proximal area) yet only at a rate of 1ϕ for each 250 km in the Mediterranean Sea (coarse mode in distal area, Fig. 4) indicating a strong variation in the rate of grain size decay of the products associated with the plinian fall phase. Notwithstanding the lack of data at intermediate distance from the source, the proximal and distal trends shown in Fig. 4 indicate a break in slope between 100 to 400 km from the vent probably reflecting a change of settling law; i.e.

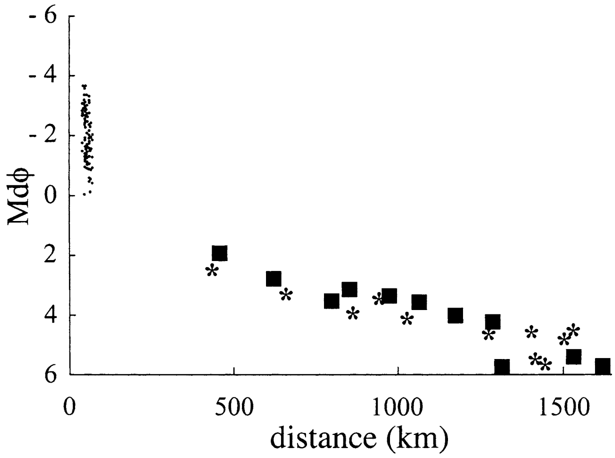

Fig. 4. Median grain size as a function of the distance from the source area for the Y-5 ash layer (asterisk: coarse mode, square: fine mode; data from *Sparks* and *Huang*, 1980; *Cornell* et al., 1983) and PPF deposit (inset)

large particles falling at high Reynolds number near the source and small particles falling at low Reynolds number in distal regions (Bonadonna et al., 1998).

Volume estimates of plinian pumice, co-plinian and co-ignimbrite ash

Isopachs for the CI fall layers (Fig. 2a) are based on our 38 measured sections and on one lacustrine sequence from Monticchio core (*Narcisi*, 1996). Calculation of the volumes of the tephra deposit were carried out using the logarithm of thickness versus $\sqrt{A}$ plots (*Pyle*, 1989; *Fierstein* and *Nathenson*, 1992). Area determinations for each isopach were made by scanning and measuring the area enclosed within the contour lines with a CAD software; we do thus not approximate the real shape to a simple (circular or elliptical) shape. The volume calculated with the cumulative fallout isopach is 4.03 km^3. This value is significantly different compared to the 15 km^3 obtained by *Rosi* et al. (1999), probably as a result of the unconstrained contour of their isopachs along the dispersal axis. As discussed by *Fierstein* and *Nathenson* (1992) the method that we have adopted provides a good estimate of the volume of the fallout deposits if there are adequate isopach data (proximal to distal dispersion well represented). In well preserved tephra fall deposits a plot of ln Th vs $\sqrt{A}$ typically shows two or three discrete segments with well defined inflection points (e.g. Quizapu 1932 fall deposit, *Hildreth* and *Drake*, 1992). The value of the slope of each segment is inversely related to the area enclosed by the isopach (e.g. steeper proximal slopes). If isopach data are limited to relatively proximal regions the volume could therefore be significantly underestimated. Thus, the lack of a 'break in slope' in the straight line on Fig. 5 indicates that the calculated volume is a minimum value. We could evaluate the total volume by adding the areas of distal isopachs to our calculation. As thickness

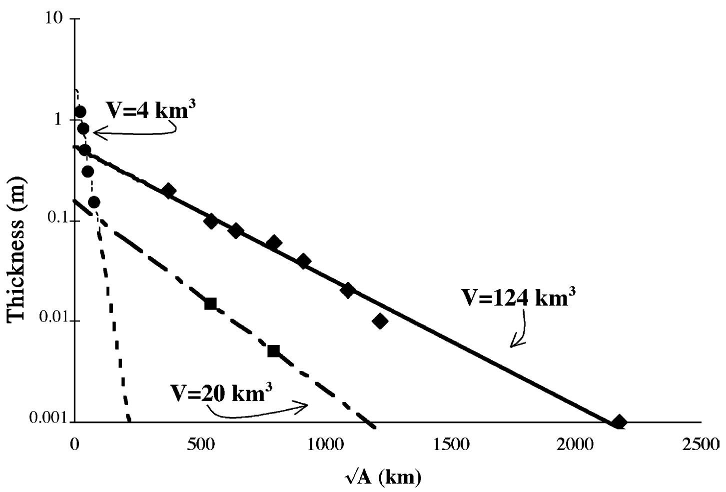

Fig. 5. Plot of thickness (ln scale) versus $\sqrt{A}$ (after *Pyle*, 1989; *Fierstein* and *Nathenson*, 1992). Dashed line represents simple exponential thinning of proximal isopachs data (circles); solid line represents the straight-line of the whole distal ash fall deposit (coarse and fine mode, diamonds), dashed and dotted line represents the segment related to the co-plinian distal ash fall deposit (squares)

data are only available for the Mediterranean Sea, we have extrapolated the data of *Cornell* et al. (1983) from the Mediterranean Sea on land assuming a minimum thickness of 1 mm for the distal sites covered by this tephra layer (i.e. north-eastern Europe). A calculated volume of 124 km^3 of tephra is thus obtained. Previous estimates of Y-5 volume range from 37 km^3, related to roughly half the total ashfall deposit distribution (*Cornell* et al., 1983), to 65 km^3 within the 1 cm contour and an estimated total volume in excess of 100 km^3 (*Thunnel* et al., 1979). All these previous estimates do not discriminate between the co-plinian and co-ignimbrite components. However, previous grain-size analyses and computer simulations indicate a large contribution of co-ignimbrite ash fall to the formation of the Y-5 layer. Our new data on proximal isopachs confirm the important role of co-ignimbrite ash fall to the total ash fall volume. The plot ln T vs $\sqrt{A}$ (Fig. 5) shows that the distal straight-line segment intersects the proximal straight-line segment at too high a value of thickness; this is because the more proximal isopach of the Y-5 ash fall deposit in the Mediterranean Sea (20 cm) is thicker than the more distal isopach of the plinian pumice deposit on land (10 cm). Our land data combined with distal measurements prove that there are two different sources (related to different eruptive phases) that contribute to the distal ash fall deposit. This is also confirmed by the trends shown in Fig. 6 where the dispersal of the distal coarse ash follows the same trend as the proximal pumice fall. The striking inflection at ~20 cm indicates that the finer part of the distal ash fall deposit increases the area covered by one order of magnitude. This is consistent with the emplacement of a co-plinian fall deposit associated with the proximal plinian products that differs from a significantly more dispersed co-ignimbrite fine, ash fall deposit. In addition, in Fig. 6

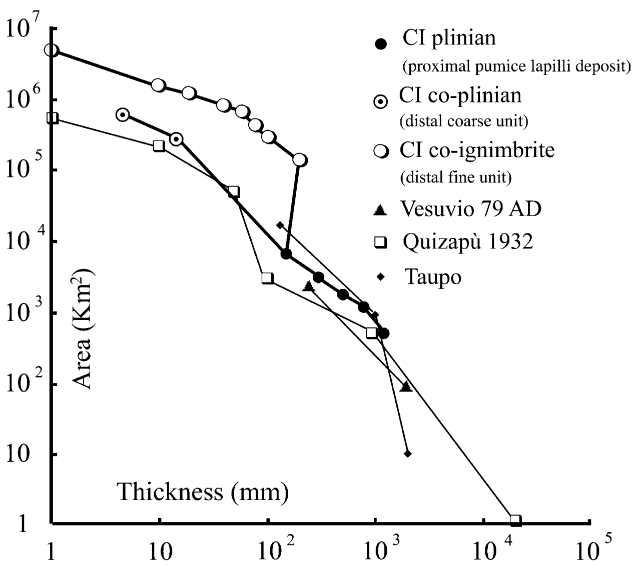

Fig. 6. Areas in km^2 enclosed by thickness isopachs in mm for plinian, co-plinian and co-ignimbrite deposits of the CI eruption. Note the different trends of the co-plinian and co-ignimbrite dispersions. For comparison, data for three other well characterized plinian eruptions are shown: Vesuvius 79AD (*Sigurdsson* et al., 1985; *Carey* and *Sigurdsson*, 1987); Taupo (*Walker*, 1980); Quizapu 1932 (*Hildreth* and *Drake*, 1992)

areas enclosed by isopachs are compared with corresponding data for three other plinian deposits illustrating the large magnitude of the CI eruption. To evaluate the volume of the co-plinian fall phase we have considered the thickness of the lower coarse unit of the Y-5 tephra where it can be clearly distinguished from the finer upper part. This approach is conservative because the more distal unstratified, bimodal deposit could be interpreted as a reworked layer (due to bioturbation and slumping effects) formed in part during the plinian phase of the eruption. The estimated total volume is almost 20 km^3 (4 km^3 of which represent the proximal accumulation); the break-in-slope is far away from the source, at $\sqrt{A} =$ 110 km (the last isopach on land has an $\sqrt{A}$ value of 80 km). Consequently the volume of the co-ignimbrite ash fall is approximately 100 km^3.

The ratio between co-plinian and co-ignimbrite ash volumes for the CI eruption can be given as 1:5; the percentage of the co-plinian ash volume can range for plinian eruptions from nearly 100% as calculated for the 1932 Quizapu eruption (*Hildreth* and *Drake*, 1992) to less then 10% as defined for the deposit related to the Tambora 1815 eruption (*Sigurdsson* and *Carey*, 1989).

Summary and conclusions

The plinian, stratified fall deposit associated with the Campanian Ignimbrite (CI) eruption is the most widely dispersed fall deposit in the Mediterranean region. In the proximal area it is composed of four pumiceous layers (A to D from base to top) having different grain size, texture and components. This sequence is capped by a succession of thin layers of contrasting grain size and higher lithic content (layer E). A widespread ash layer found in the eastern Mediterranean Sea (Y-5 tephra) and in many countries in eastern Europe is associated with the CI eruption. In this paper a general distribution map of this tephra layer is presented. Furthermore, we were able to discriminate between the plinian and ignimbrite contribution to this distal ash fall deposit and to calculate the volumes of the proximal plinian, distal plinian (co-plinian) and co-ignimbrite deposits.

From a hazard point of view, the most striking consequence of an eruption of such magnitude and dispersal power is its elevated destructive potential. The proximal region collapsed as a consequence of caldera formation, while a wider area was buried beneath a thick fall deposit and successively devastated by a huge pyroclastic flow that emplaced the Campanian Ignimbrite. Ash fall particles associated both with the plinian and the ignimbrite phases of this eruption were deposited over a huge region encompassing eastern Europe and the Mediterranean Sea. By comparison with other historic plinian events (e.g. the Tambora 1815 eruption) we argue that the enormous amounts of ash and aerosols ejected during the CI eruption must have been carried around the world by high-altitude winds, affecting the intensity of solar radiation and possibly resulting in short-lived climate changes.

Acknowledgements

Part of this work was carried out within the scope of a postdoctoral fellowship (C.S.). We are grateful to all those who helped us, in many seasons, to find outcrops of CI fall deposit, especially *Mr. Bartolini*. We also thank *G. Mastrolorenzo* and *L. Ruvo* for revising the manuscript. Careful reviews by *P. Cole* and an anonymous reviewer helped to better focus the manuscript.

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