Physical characteristics of tephra layers in the deep sea realm: the Campanian Ignimbrite eruption

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Abstract: Tephra deposits in the deep sea can survive undisturbed for long periods of time and, on regional scales, tend to be much better preserved than their subaerial counterparts. In this study, grain size distributions and thicknesses of tephra deposits from the Campanian Ignimbrite (CI) eruption (39 000 yr BP; magnitude c. 7.7) preserved in thirty-three deep sea cores are analysed to infer key eruption parameters. Distal deep sea tephra thickness data show an exponential decrease with distance from source. Such trends are difficult to identify in distal subaerial data owing to reworking and limited exposure. We find that tephra grain size distributions are much less affected by depositional environment than thickness, with trends that are consistent across distal subaerial, lacustrine and deep sea environments. The CI layer exhibits bimodal grain size distributions to distances of c. 1000 km, after which it becomes unimodal. Such trends can be related to different mechanisms of tephra transport in the atmosphere, whereby at proximal to medial distances the Plinian and co-ignimbrite phases produce distinct plumes. Within 150 and 900 km from source, Plinian tephra constitutes 40 ± 5% of the deposit volume. Beyond this region where coarse particles are deposited, the plumes merge and fines derived largely from co-ignimbrite elutriation are spread in the atmosphere at velocities greater than the settling velocities of the particles.

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The Campanian Ignimbrite (CI) eruption

The CI eruption is the largest known Quaternary eruption in Europe (Ninkovich & Heezen 1967; Barberi et al. 1978). Analysis of grain size and thickness of the proximal deposits indicates the source of the eruption is located within the Phlegraean fields area of southern Italy (Perrotta & Scarpati 2003; Fig. 1). Both caldera and fissure origins have been suggested, although the exact location of the vent is unknown. The eruption is dated as 39 ± 0.4 ka BP (De Vivo et al. 2001; Ton-That et al. 2001).

The eruption produced a sequence of deposits, with two proximal pumice fall units and a major ignimbrite that can be divided into numerous stratigraphic subunits (Rosi et al. 1999; Perrotta & Scarpati 2003). Geochemically, the deposits are homogeneous with a compositional range from phonolite to trachyte. Pyle et al. (2006) suggested that the eruption evacuated a chemically zoned magma body with a volumetrically dominant and chemically evolved phonotrichyte tapped throughout the eruption, bounded by a less-evolved trachytic layer at the beginning and end. Plume heights in the Plinian phase reached 44–45 km (Pyle et al. 2006), dispersing tephra with a particularly high content of fine bubble-wall shards (Pyle et al. 2006; Sulipzio et al. 2010). These glass shards are distinctive with long, straight to slightly curved plates (Pyle et al. 2006). Such aerodynamic shapes are thought to have aided tephra dispersion to great distances.

Tephra deposits correlated with the CI eruption have been discovered in the mainland of Central Italy (Narcisi 1996; Frezzotti & Narcisi 1996), in Northern Italy (Chiesa et al. 1990), Bulgaria (Harbkovska et al. 1990), Albania (Wagner et al. 2008; Sulipzio et al. 2010), Greece (Vitaliano et al. 1981; St. Seymour & Christianis 1995), Russia (Mekhestev et al. 1984; Pyle et al. 2006), Romania (Constantin et al. 2012; Veres et al. 2013; Fitzsimmons et al. 2013) and Montenegro (Morley & Woodward 2011) covering an area of at least 2 × 10⁶ km² (Fedele et al. 2002; Pyle et al. 2006; Giaccio et al. 2008). Difficulties in volume estimation of the CI deposits arise owing to the unknown depositional limits and correlation of the Plinian and ignimbrite/co-ignimbrite phases, particularly at distance. As such, volume estimates for the CI vary by a factor of 2 and have increased, as more tephra deposit sites have been identified. An overview of estimated volumes is provided by Pyle et al. (2006), who estimated a total volume dense rock equivalent (DRE) for both the Plinian and the ignimbrite phase of between 105 and 210 km³.

The CI tephra layer in deep sea cores

Within deep sea deposits from the Mediterranean Sea, the CI deposit is known as the Y5 (e.g. Ton-That et al. 2001) or C13 (Thunell et al. 1979) horizon. The Y5 is the most widespread tephra of the Eastern and Central Mediterranean region (Keller et al. 1978; Gallo et al. 1980; McCoy 1981; Vinci 1985; Paterni et al. 1986, 1988, 1990; Cramp et al. 1989; Vezzoli 1991). In early studies, the CI tephra in deep sea cores was labelled the ‘Lower’ tephra layer by Ninkovich & Heezen (1967). The layer was geochemically correlated with the 25 kyr eruption of Ischia Islands using samples from Salina Island, and was stratigraphically correlated throughout the Mediterranean Sea. Thunell et al. (1979) re-analysed the tephra layer and compared the geochemical characteristics with those from proximal deposits of the Campanian Ignimbrite eruption and found a much better correlation. Therefore, the ‘Lower’ tephra layer was instead attributed to the CI eruption. Reanalysis of the geochemical characteristics of ash layers in the Mediterranean has shown that glass chemistry is often not unique to an eruption (Turney et al. 2008; Smith et al. 2011). Therefore other characteristics, for example the stratigraphy, chronology of the core and the magnitude of the eruption, are taken into account when assessing tephra provenance (Turney et al. 2008; Smith et al. 2011; Tomlinson et al. 2012).
Fig. 1. (a) Map of the Mediterranean showing the approximate source of the CI eruption (Star) and subaerial sampling locations. The dashed line encloses the known extent of the eruption (modified from Giaccio et al. 2008 and Pyle et al. 2006). (b) Locations of the deep sea cores analysed in this study (see Table 1 for further information). Circles represent locations where the deposit is bimodal while square symbols identify locations where the deposit is unimodal.
Previous grain size analysis of deposits from deep sea cores was conducted by Sparks & Huang (1980) and Cornell et al. (1983). Both studies sieved the coarse fraction of the deposits. For the fine fraction, Cornell et al. (1983) used a Particle Data electro-resistance size analyser, whereas Sparks & Huang (1980) used a Coulter counter. Both methods rely on the electrical resistivity of particles. These studies noted a distinct bimodal character to deposits less than 800 km from source. Sparks & Huang (1980) commented that deposits at 440 and 630 km can be separated into a coarse lower unit dominated by elongate pumice separated by a sharp boundary from a fine-grained volcanic glass upper unit. Based on these physical differences the coarse pumice layer was attributed to the Plinian phase of the eruption and the fine-grained upper unit to the co-ignimbrite phase. With distance from source they describe mixing of these units and therefore difficulty distinguishing the separate units. In addition, both studies note that the coarse component decreases in size away from source, whereas the fine mode shows little change in median diameter with distance, residing at about 13 μm (Cornell et al. 1983). The studies showed the distal (> 800 km from source) deposits were unimodal.

Both studies interpreted the coarse mode as being from the Plinian phase of the eruption, while the fine mode represents tephra elutriated from large-scale pyroclastic density currents during the co-ignimbrite phase of the eruption. Some studies (e.g. Brazier et al. 1983) attribute the bimodal grain size character of such deposits to aggregation, where the fine mode represents particles that are deposited much closer to source than would be expected if individual particulate settling was dominant. More recent studies have shown that the physical origin of CI tephra can be determined using glass chemistry (Tomlinson et al. 2012). However, it is not yet possible to determine whether a deposit is co-ignimbrite or Plinian by analysing physical characteristics such as grain size and morphology alone.

**Methodology**

Thirty-three deep sea cores from cruises MD81, TR171, TR172, Vema 10, Vema 14, Robert Conrad (RC) 9 and KET were analysed (Table 1). These cores sample the dispersal area across the Mediterranean Sea (Fig. 1). The cores were inspected to identify the CI tephra. Subaerial samples from Lago Grande di Monticchio (Wulf et al. 2004), San Gregorio di Magno (Munno & Petrosino 2007), Franchi Cave (Vitaliano et al. 1981), Megali Limni on the Island of Levos (Margarri et al. 2007), Tenaghi Philippon peat bog (Müller et al. 2011), loess from Romania (Veres et al. 2013) and re-worked samples from Russia (Pyle et al. 2006) were also analysed.

The thickness of the deposit was measured in each core and the amount of bioturbation was estimated. Where possible, for each of the deep sea cores, samples were taken at 1 cm intervals through the CI layer. Carbonate material was removed by covering the samples with 1 M acetic acid for 24 h. Organic material was removed from subaerial samples by placing each sample in 30% hydrogen peroxide for 72 h. Samples were then cleaned three times using a centrifuge at 4000 rps for 20 min.

Grain size was measured using the Malvern Mastersizer 2000 at the Graduate School of Oceanography, Rhode Island University. The method measures grain size by laser diffraction whereby the angle of refraction of light off a particle is inversely proportional to its grain size. The samples were suspended in deionized water with sodium hexametaphosphate and were placed in an ultrasonic bath to discourage formation of aggregates. Three aliquots were taken for each sample and the average is reported. Results are presented in the form of percentage volume of sample, for example, if a result indicates that 25% of the distribution is within a certain size category, this means that the total volume of all particles with diameters in this ranges represents 25% of the total volume of all particles in the distribution.

The deposits within Lago Grande di Monticchio cores J10 and O10 (Fig. 2) were sampled at 1 cm intervals except where changes in stratigraphy could be identified. Within this core, the deposit can be split into two units. Wulf et al. (2004) attributed the lowermost layer to the Plinian phase of the eruption, and the overlying layer to the co-ignimbrite phase of the eruption. Samples from the Plinian fall deposit at Lago Grande di Monticchio were too coarse to measure using the Malvern Mastersizer. These samples were sieved at half-phi intervals down to 90 μm. The material less than 500 μm was also measured using the Malvern Mastersizer and the two datasets were weighted and combined for each of the samples following Eychenne et al. (2012).

**Results**

Within the Lago Grande di Monticchio cores, the tephra is easily separated into Plinian and co-ignimbrite fall deposits separated by a sharp boundary (Fig. 2). The Plinian deposit contains highly vesiculated and elongate buff coloured pumice with abundant lithics and crystals of sandine, pyroxene and biotite. The co-ignimbrite fall deposit is much finer and is completely composed of glass shards.

The CI layer at medial distances (400–800 km) is composed of elongate pumice fragments, biotite
and vitreous glass. At distances greater than 800 km the pumice component is no longer present and the deposit is made up of glass shards (Fig. 3). The deposit is often pale yellow/grey in colour (Munsell colour 2.5Y/8.1). Many of the deposits show a bioturbated top such as LC21 (Fig. 3).

Table 1. List of locations of samples of the CI tephra layer that have been analysed in this study; asterisks denote reworked deposits; numbers of deep sea cores correlate with those in Figure 1

| Sample/core | N   | E   | Depositional environment | Water depth | Depth in core (base; m) | Distance from source (km) | Thickness (cm) |
|-------------|-----|-----|--------------------------|-------------|-------------------------|---------------------------|----------------|
| 1           | LGM J10 P | 40.93 | 15.61 | Lake | Not known | – | 130 | 16.5 |
|             | LGM J10 co-I | 40.93 | 15.61 | Lake | Not known | – | 130 | 13 |
|             | LGM J10 T | 40.93 | 15.61 | Lake | Not known | 25 | 130 | 29.5 |
| 2           | LGM O10 P | 40.93 | 15.61 | Lake | Not known | – | 130 | 17.5 |
|             | LGM O10 co-I | 40.93 | 15.61 | Lake | Not known | – | 130 | c. 23.5 |
|             | LGM O10 T | 40.93 | 15.61 | Lake | Not known | 25 | 130 | c. 41 |
| 3           | SGM | 40.65 | 15.43 | Lake | Not known | 8.5 | 110 | 60 |
| 4           | ML00 | 39.1 | 26.33 | Lake | Not known | 7.6 | 1060 | 16 |
| 5           | ML01 | 39.1 | 26.33 | Lake | Not known | 5.63 | 1060 | 8 |
| 6           | ML2A | 39.1 | 26.33 | Lake | Not known | 5.54 | 1060 | 37 |
| 7           | ML2B | 39.1 | 26.33 | Lake | Not known | 5 | 1060 | 12 |
| 8           | Franchi Cave | 37.51 | 22.96 | Cave | NA | NA | 850 | – |
| 9           | Phillipon | 40.97 | 24.22 | Peat bog | NA | 12.81 | 850 | 19 |
| 10          | Dragnesti-OLT | 44.16 | 24.54 | Loess | NA | NA | 940 | <60* |
| 11          | Caciulastesti | 43.94 | 23.94 | Loess | NA | NA | 880 | <60* |
| 12          | Boschevo | 51.4 | 39 | Loess | NA | NA | 2300 | 1–2 |
| 13          | Kostenki | 51.4 | 39 | Loess | NA | NA | 2300 | <10 |
| 14          | LC21 | 35.66 | 26.58 | Deep sea | 1522 | 4.8 | 1234 | 10 |
| 15          | TR171-21 | 34.45 | 20.13 | Deep sea | 2785 | 0.25 | 900 | 1.5 |
| 16          | TR171-22 | 34.1 | 21.36 | Deep sea | 2380 | 0.38 | 997 | 3.5 |
| 17          | TR171-27 | 33.83 | 25.99 | Deep sea | 2680 | 1.13 | 1312 | 1.5 |
| 18          | TR171-28 | 34.85 | 26.39 | Deep sea | 2075 | 1.27 | 1273 | 0.2 |
| 19          | TR172-11 | 34.14 | 28.98 | Deep sea | 2585 | 1.03 | 1510 | 1.5 |
| 20          | TR172-12 | 33.9 | 29.26 | Deep sea | 2930 | 5.52 | 1550 | 0.8 |
| 21          | TR172-18 | 34.22 | 29.56 | Deep sea | 3116 | 0.39 | 1550 | 1 |
| 22          | TR172-19 | 34.71 | 30.15 | Deep sea | 2354 | 1.28 | 1570 | 1 |
| 23          | TR172-21 | 35.21 | 29.76 | Deep sea | 2650 | 0.83 | 1509 | 1.7 |
| 24          | TR172-22 | 35.32 | 29.02 | Deep sea | 3150 | 1.45 | 1445 | 2 |
| 25          | TR172-24 | 34.88 | 28.46 | Deep sea | 2600 | 1.53 | 1427 | 1 |
| 26          | TR172-42 | 40.03 | 14.55 | Deep sea | 728 | 4.05 | 118 | 35 |
| 27          | KET 8022 | 40.58 | 11.7 | Deep sea | 2430 | 3.2 | 300 | 12 |
| 28          | DED 8708 | 39.67 | 13.57 | Deep sea | 6.18 | 200 | 35 |
| 29          | RC9 190 | 38.65 | 19.23 | Deep sea | 1712 | 1.31 | 497 | 4.5 |
| 30          | RC9 191 | 38.2 | 18.03 | Deep sea | 2345 | 3.1 | 445 | 4 |
| 31          | RC9 183 | 34.5 | 23.42 | Deep sea | 2684 | 1.22 | 1066 | 3 |
| 32          | RC9 189 | 36.98 | 19.68 | Deep sea | 3378 | 1.38 | 645 | 9 |
| 33          | RC9 181 | 33.42 | 25.02 | Deep sea | 2286 | 1.03 | 1264 | 1.5 |
| 34          | RC9 179 | 34.27 | 27.18 | Deep sea | 2604 | 1.42 | 1360 | 1 |
| 35          | RC9 185 | 34.45 | 20.12 | Deep sea | 2858 | 1.15 | 890 | 3 |
| 36          | V10 48 | 37.73 | 25.58 | Deep sea | 833 | 3.61 | 1050 | 4 |
| 37          | V10 49 | 36.08 | 26.83 | Deep sea | 1170 | 2.2 | 1200 | 10 |
| 38          | V10 58 | 35.67 | 26.3 | Deep sea | 2283 | 6.8 | 1205 | 10 |
| 39          | V10 60 | 35.82 | 28.97 | Deep sea | 4081 | 4 | 1400 | 1.8 |
| 40          | V10 67 | 35.7 | 20.72 | Deep sea | 2904 | 1.3 | 810 | 4.5 |
| 41          | V10 68 | 36.9 | 17.95 | Deep sea | 3455 | 1.84 | 550 | 9 |
| 42          | V10 69 | 37.23 | 17.28 | Deep sea | 3156 | 1.8 | 490 | 3 |
| 43          | V10 26 | 36.27 | 21.6 | Deep sea | 3515 | 0.96 | 830 | 2 |
| 44          | V14 132 | 35.77 | 23.4 | Deep sea | 2750 | 1.2 | 1100 | 0.1 |

Abbreviations: LGM, Lago Grande di Monticchio where P is Plinian; co-I, co-ignimbrite, T, total; SGM, San Gregorio di Magno; ML, Megali Limni.
Fig. 2. The Campanian Ignimbrite (CI) within cores (a) J10 and (b) O10 from Lago Grande di Monticchio (130 km from source). The Plinian deposit is separated from the overlying co-ignimbrite ash by a sharp boundary; images courtesy of S. Wulf.
Thicknes

The thickness at each location is plotted alongside previously published data (Fig. 4). The plot shows a large range in thickness of the Plinian fall deposit close to source (<50 km). No measurements of co-ignimbrite thickness at these proximities are published. The Lago Grande di Monticchio (130 km from source) cores contain both Plinian fall and co-ignimbrite fall deposits, but owing to their distance from source and elevation are not thought to contain primary ignimbrite. Measurements for these thicknesses are plotted separately. For the more distal deposits it was not possible to separate the Plinian and co-ignimbrite layers, and therefore total thickness is plotted.

There is a large range in thickness of the deposit in distal subaerial environments, with most deposits typically much thicker than for equivalent deep sea deposits. This variability is attributed to reworking (e.g. Pyle et al. 2006) and, for this reason, regression was applied to the deep sea thickness measurements only. The thickness of the tephra layer is consistent with an exponential decrease with distance from source (Fig. 4). Prediction of the deposit thickness at 130 km using this exponential trend gives a thickness that is less than that seen at Lago Grande di Monticchio but within 95th percentile confidence levels determined by the deep sea deposits.

Grain size

Grain size distributions were obtained for each sample. At Lago Grande di Monticchio, 130 km from source, the deposit can be separated into a lower coarse-grained bimodal (modes between 620 and 590 μm) Plinian deposit overlain by a fine (25–30 μm) unimodal co-ignimbrite fall deposit. Deposits between 400 and 1000 km from source (e.g. RC9–190, 490 km; Fig. 5) cannot be divided into separate units but show distinct grain size bimodality. The bimodality varies with depth in each deposit. The coarse mode is dominant at the base
of the deposit, with the fine mode becoming more prevalent at the top. In addition, the coarse mode becomes finer with decreasing depth in the deposit, whereas the fine mode does not change with depth. Distal deposits (>850 km) are unimodal (Fig. 5), and deposits show very similar grain-size distributions independent of depositional environment. The exception to this is that of Franchi Cave, which is much coarser than all other deposits at similar distances from the source. This is attributed to the removal of fines by wind. The results obtained from analysis of subaerial deposits from Russia are identical to those shown by Pyle et al. (2006).

The grain size modes of the deposits are shown in Figure 6. Where multiple samples were taken from a single deposit, the weighted individual sample grain size distributions were averaged to produce a single size distribution. The fine and coarse modes for bimodal samples are plotted separately. In agreement with results of previous studies, the coarse mode becomes finer with distance from source, and this can be described by an exponential function. However, somewhat counter-intuitively, the fine mode becomes coarser with distance from source. This is highlighted when grain size distributions of the co-ignimbrite deposit at Lago Grande di Monticchio and the fine mode at distance are compared. By correlating the deposits at Lago Grande di Monticchio with more distal deposits, it is possible to determine the physical provenance of the distal subpopulations. Based on the above trends, we correlate the coarse mode with the Plinian and the fine mode with the co-ignimbrite phase of the eruption.

The deposit becomes unimodal at c. 850 km from the source. The mode of different deposits varies between 45 and 80 μm, much coarser than the fine mode of 13 μm measured by Cornell et al. (1983). This can be attributed to the different methods by which results are recorded and presented. The previously published data are based on the number of particles of a given grain size rather than the volume of the particles. Fitting a regression to the unimodal deposits suggests a slight decrease in grain size mode with distance from source. The very distal subaerial deposits are coarser than would be expected at such distances based on regression using the deep sea tephra samples, but are within uncertainty limits.

The equations generated by fitting the coarse and fine mode data of the bimodal deposits indicate convergence at a distance of 1400 km from source. However, deposits at distances of 850 km from source are unimodal. This indicates that between 850 and 1400 km the difference between the two grain size subpopulations which comprise the total grain size distribution is so minor that the deposit appears unimodal. Analysis of multiple samples from a single unimodal deposit shows that, between 850 and 1500 km from source, there is a distinct change in mode from the base of the deposit to the top. Tephra at the base are much coarser than at the top of the deposit. This trend is clearly illustrated when comparing grain size distributions from the top and base of the deposit in deep sea core LC21 (Fig. 3c). Between 850 and 1400 km, the grain size at the base of the deposit (the coarser mode) decreases with distance from source, while the
grain size at the top of the deposit (the finer mode) increases. These trends closely follow those of the separate modes from the bimodal deposits, showing that the coarse Plinian component is present to distances of at least 1425 km.

The grain size distributions were converted to cumulative distributions and the 95th percentile was used to represent the maximum grain size and show trends in the coarse tail of the grain size distribution with distance from source (Fig. 7). Maximum grain size shows a decrease with distance from source and can be well represented by an exponential trend. Even at great distance, where deposits are unimodal and where there is little change in mode, there is still a decrease in maximum grain size. The median grain size trend follows the trends in the 95th percentile closely, but there is much more scatter in these data.

The Kware Geological Software SFT application (sequential fragmentation/transport; Wohletz et al. 1989) was used to deconvolve the grain size distributions of each of the bimodal deposits into a number of separate subpopulations. In applying SFT, it is assumed that the component

Fig. 5. (a) Grain size results from deep sea core RC9-190, 500 km from source, showing upward fining. The coarse mode and volumetric fraction of the coarse population decrease throughout the deposit whereas the fine mode stays constant. (b) A representative sample of grain size distributions from deep sea cores and subaerial environments at different distances from source, showing a striking similarity in grain size distributions, despite different depositional environments. The exception is tephra from Franchi Cave, Greece, whose coarse distribution is attributed to winnowing removing fines.
subpopulation distributions follow a log–normal distribution. Similar analyses of deposits from Mt St Helens (Rose & Durant 2009) and Volcan de Colima (Evans et al. 2009) have enabled identification of subpopulations, especially of fine ash, and consequently implications for atmospheric dispersal. Here, a maximum number of three subpopulations were used such that the integrated residuals between the data and modelled subpopulation equaled less than 5%.

The deposit at Lago Grande di Monticchio can be separated into three subpopulations. The bimodal Plinian fall deposit was separated into two constituent distributions and these modes are plotted separately as subpopulations 1A and 1B. The grain size of the co-ignimbrite fall varies little throughout the deposit and is unimodal. This is plotted as subpopulation 2.

The best fit to the bimodal deep sea tephra was achieved using three subpopulations (Fig. 8a, Table 2). The coarse subpopulation (population 1) mode varies between 300 and 140 μm and the data can be described by an exponential decrease with distance from source. The middle subpopulation

Fig. 6. (a) Grain size mode with distance from source. The coarse mode is described by an exponential decrease with distance from source \( (y = 721.0e^{-0.002x}; R^2 = 0.9) \). The fine \( (y = 27.7e^{-0.0004x}; R^2 = 0.2) \) and unimodal \( (y = 75.7e^{-1E-04x}; R^2 = 0.1) \) modes describe an exponential increase and slight exponential decrease, respectively. (b) Mode of deposit extremities. The solid symbols represent the coarse and fine modes of the bimodal samples. The open symbols represent samples from unimodal deposits displaying a change in mode from the base to the top of the deposit. The coarse mode depicts an exponential decrease \( (y = 603.6e^{-0.002x}; R^2 = 0.9) \), while the fine mode again describes an exponential increase with distance from source \( (y = 28.6e^{0.004x}; R^2 = 0.2) \).
The volumetric fraction of each subpopulation relative to the total sample is illustrated in Figure 8b. The fraction of the deposit composed of subpopulation 1 and 2 varies significantly with distance from source. Between 400 and 700 km there is no clear trend in the data. At distances greater than 800 km, subpopulation 1, the population associated with the Plinian phase of the eruption, is still present but increasingly becomes the minor fraction. There is very little change in subpopulation 3 with distance from source. Assuming that the coarse mode represents the Plinian phase of the eruption and the fine mode the co-ignimbrite phase, it is possible to calculate the relative proportions of the separate phases. Integration of data shown in Figure 8 between 130 and 900 km show that the Plinian material constitutes 40 ± 5% of the tephra while co-ignimbrite material comprises 60 ± 6%. To date, there have been no studies that have quantified the proportion of eruptive phases within distal deposits and as such there are no figures with which to compare these results. Previous studies have highlighted the difficulties in attributing distal deposits to either Plinian or co-ignimbrite phases, for example, deposits from the 1815 eruption Tambora (Self et al. 2004; Sigurdsson & Carey 1989). Here we are able to show that the Plinian ash constitutes a great proportion of the CI deposit at distance with significant implications for ash dispersal. It is not possible to quantitatively determine the relative proportions of tephra from the different phases at distances greater than 900 km owing to the unimodal nature of the deposits. The rapid decrease in Plinian component between 800 and 900 km indicate that it is minor.

Discussion

Changes in the physical characteristics of tephra with distance from source can be used to infer key eruptive parameters and constrain how tephra is transported through the atmosphere and ocean. Analysis of deposits from a range of environments has shown that those in the deep sea are more reliable than those on land with regards to capturing trends, particularly the thickness characteristics. This is despite the potentially large influence of bioturbation, slumping and effects of currents on deep sea deposits (McCoy 1981). The grain size distributions of the CI deposits reflect the plume
dynamics of the Plinian and co-ignimbrite phases. Analysis of the CI deposits at Lago Grande di Monticchio, in addition to deconvolution of distal grain size distributions, allow the more distal coarse mode in deep sea cores to be attributed to the Plinian phase of the eruption while the fine mode is attributed to the co-ignimbrite phase. Boundaries between the Plinian and co-ignimbrite deposits are used to infer the relative timing of the phases while grain size trends provide information regarding tephra dispersion and sedimentation.

At a given distance from source, the grain size distributions in the deep sea and subaerial environments are virtually indistinguishable. For deposition in the deep sea, tephra is transported not only through the atmosphere but also through thousands of metres of water to the sea floor. Given that the settling velocity in water is significantly slower than in air (e.g. Cashman & Fiske 1991), an efficient depositional process is required to preserve the original grain size distributions. Carey (1997) and Manville & Wilson (2004) have shown that tephra

![Fig. 8. Kware sequential fragmentation/transport (SFT) analysis results for the bimodal samples. Each of the sample grain size distributions was separated into three log–normal distributions. (a) The change in mode of the distributions with distance from source. (b) Fraction of subpopulations in each sample with distance from source.](image-url)
in the deep sea environment is deposited as vertical density currents. Tephra accumulates at the air–sea interface owing to the differential settling velocity until Rayleigh–Taylor instabilities develop owing to local reversals in density stratification. Vertically descending plumes then deliver the tephra to the bottom waters. By this process, the tephra is deposited much more quickly than when only Stoke’s law settling is considered, enabling fines to be preserved in the deposits. Further evidence is provided by analysis of settling rates of ash in the South China Sea after the Pinatubo eruption (Weisner et al. 1995).

Thickness measurements of the CI deposits in the deep sea realm can be described by exponential thinning. Such trends are a common observation in volcanic fall deposits (e.g. Thorarinsson 1954; Pyle 1989). It is difficult to reconcile thickness data from subaerial deposits with those from deep sea deposits. We have shown that, except with regards to constraining the extent of dispersal, there are no extra benefits to focusing on subaerial deposits. In addition, the limited number of distal subaerial locations where the tephra is found makes drawing isopach maps difficult and hampers estimation of erupted volume. Recent volume estimates of the CI eruptions (e.g. Costa et al. 2012) are based on the fit of an advection–diffusion tephra dispersion model to thickness data. However, large uncertainties remain when fitting such models to distal subaerial deposits and therefore volume estimates contain large uncertainties. Although the co-ignimbrite tephra is volumetrically dominant, it may not be feasible to fit distal deposits assuming only a single component and plume.

The grain size distributions can be interpreted to infer information regarding eruption dynamics. The rate of change in the coarse mode can be attributed to a number of different factors. These include volumetric flux, plume height, clast shape and the influence of wind. The presence of bimodal distributions is commonly attributed to aggregation of fine ash (e.g. Brazier et al. 1983) whereby the fine population is deposited as particle aggregates and the coarse population is due to the fallout of individual particles. Comparison of the distal deposits with those at Lago Grande di Monticchio shows that aggregation alone cannot explain bimodality in medial deposits. The presence of a distinct co-ignimbrite layer at Lago Grande di Monticchio suggests that fine ash from this eruption was deposited after the Plinian deposit. The correlation of the distal fine mode with the co-ignimbrite deposit at Lago Grande di Monticchio indicates that, for this eruption, the bimodal distribution represents the separate phases of the eruption. The concentration of fines so close to source indicates that aggregation played a significant role in deposition of the fine population.

Another interesting observation is the increase in fine mode with distance from source. The deposit at Lago Grande di Monticchio (c. 30 μm) is considerably finer than the more distal ash (50–80 μm). With greater distance, the fine mode becomes coarser still, as shown from the top of the unimodal deposits between 850 and 1400 km. This could be attributed to two processes; (1) mixing of coarse Plinian ash with co-ignimbrite ash in the atmosphere at distance; and (2) the full grain size distribution of the co-ignimbrite phase is deposited at Lago Grande di Monticchio owing to proximity to source and very high concentrations of tephra in the atmosphere at these

### Table 2. Kware sequential fragmentation/transport (SFT) results for bimodal samples, with their subpopulations (μm) and associated fractions

| Sample      | RC9-185 | RC9-189 | RC9-190 | RC9-191 | TR171-21 | V10-67 | V10-69 |
|-------------|---------|---------|---------|---------|----------|--------|--------|
| Distance (km) | 885     | 645     | 497     | 445     | 900      | 811    | 487    |
| Thickness (cm) | 3       | 10      | 4       | 4       | 2.5      | 4.5    | 0.5    |
| Subpopulation 1 (μm) | 174     | 142     | 281     | 297     | 158      | 160    | 308    |
| Subpopulation 1 fraction | 0.25    | 0.52    | 0.35    | 0.39    | 0.13     | 0.35   | 0.46   |
| Subpopulation 2 (μm) | 49      | 29      | 46      | 44      | 41       | 35     | 45     |
| Subpopulation 2 fraction | 0.68    | 0.4     | 0.59    | 0.56    | 0.77     | 0.59   | 0.42   |
| Subpopulation 3 (μm) | 4       | 4       | 3       | 3       | 3        | 4      | 4      |
| Subpopulation 3 fraction | 0.08    | 0.08    | 0.06    | 0.05    | 0.1      | 0.06   | 0.12   |

in the deep sea environment is deposited as vertical density currents. Tephra accumulates at the air–sea interface owing to the differential settling velocity until Rayleigh–Taylor instabilities develop owing to local reversals in density stratification. Vertically descending plumes then deliver the tephra to the bottom waters. By this process, the tephra is deposited much more quickly than when only Stoke’s law settling is considered, enabling fines to be preserved in the deposits. Further evidence is provided by analysis of settling rates of ash in the South China Sea after the Pinatubo eruption (Weisner et al. 1995).

Thickness measurements of the CI deposits in the deep sea realm can be described by exponential thinning. Such trends are a common observation in volcanic fall deposits (e.g. Thorarinsson 1954; Pyle 1989). It is difficult to reconcile thickness data from subaerial deposits with those from deep sea deposits. We have shown that, except with regards to constraining the extent of dispersal, there are no extra benefits to focusing on subaerial deposits. In addition, the limited number of distal subaerial locations where the tephra is found makes drawing isopach maps difficult and hampers estimation of erupted volume. Recent volume estimates of the CI eruptions (e.g. Costa et al. 2012) are based on the fit of an advection–diffusion tephra dispersion model to thickness data. However, large uncertainties remain when fitting such models to distal subaerial deposits and therefore volume estimates contain large uncertainties. Although the co-ignimbrite tephra is volumetrically dominant, it may not be feasible to fit distal deposits assuming only a single component and plume.

The grain size distributions can be interpreted to infer information regarding eruption dynamics. The rate of change in the coarse mode can be attributed to a number of different factors. These include volumetric flux, plume height, clast shape and the influence of wind. The presence of bimodal distributions is commonly attributed to aggregation of fine ash (e.g. Brazier et al. 1983) whereby the fine population is deposited as particle aggregates and the coarse population is due to the fallout of individual particles. Comparison of the distal deposits with those at Lago Grande di Monticchio shows that aggregation alone cannot explain bimodality in medial deposits. The presence of a distinct co-ignimbrite layer at Lago Grande di Monticchio suggests that fine ash from this eruption was deposited after the Plinian deposit. The correlation of the distal fine mode with the co-ignimbrite deposit at Lago Grande di Monticchio indicates that, for this eruption, the bimodal distribution represents the separate phases of the eruption. The concentration of fines so close to source indicates that aggregation played a significant role in deposition of the fine population.

Another interesting observation is the increase in fine mode with distance from source. The deposit at Lago Grande di Monticchio (c. 30 μm) is considerably finer than the more distal ash (50–80 μm). With greater distance, the fine mode becomes coarser still, as shown from the top of the unimodal deposits between 850 and 1400 km. This could be attributed to two processes; (1) mixing of coarse Plinian ash with co-ignimbrite ash in the atmosphere at distance; and (2) the full grain size distribution of the co-ignimbrite phase is deposited at Lago Grande di Monticchio owing to proximity to source and very high concentrations of tephra in the atmosphere at these

distances. At greater distances, the coarser material (>40 μm) becomes concentrated at the base of the plume and is deposited as aggregates while finer tephra is retained and dispersed further downwind and deposited to produce cryptotephra. It is likely that both processes contribute to the coarsening trend.

The CI eruption timeline is relatively simple in comparison to other eruptions. Proximal deposits show that the eruption produced a high-intensity Plinian phase followed by multiple large pyroclastic density currents that produced voluminous co-ignimbrite clouds. Deposits give little information regarding the mechanism of eruption evolution from Plinian to ignimbrite forming, for example whether flows were produced by column collapse or were emitted from large fissures (e.g. De Vivo et al. 2001; Rolandi et al. 2003; Costa et al. 2011). The sharp boundary between the Plinian and co-ignimbrite deposits at Lago Grande di Monticchio indicates that the transition was rather abrupt, but with enough time to allow Plinian fall deposits to settle through the water column before co-ignimbrite ash was deposited. We therefore consider the eruption as forming two distinct plumes, the first being the Plinian plume and the second the co-ignimbrite plume (Fig. 9). The Plinian plume is thought to have reached 40–44 km in height (Pyle et al. 2006), injecting material with a wide grain size distribution into the atmosphere.

The tephra elutriated from pyroclastic density currents formed co-ignimbrite plumes rising 37–40 km (Costa et al. 2012) with grain size distributions much smaller and finer than those from the Plinian phase. At distances of 400–630 km from source, Sparks & Huang (1980) were able to identify Plinian deposits with a sharp upper contact separating them from an overlying co-ignimbrite deposit. At distances greater than 630 km, this contact becomes indistinct as the tephra from the two phases became mixed in the atmosphere. This indicates that the co-ignimbrite plume propagated through the atmosphere at greater speeds than the Plinian plume.

Initially both the Plinian and co-ignimbrite plumes can be modelled as intrusive gravity currents.

Fig. 9. Schematic model to show dispersion of tephra through the atmosphere. The evolution of the eruption plume can be separated into two main phases. 1. The Plinian phase where at proximal–medial distances (<500 km) the Plinian tephra is deposited (A) before (B) the co-ignimbrite cloud arrives. Close to source (B1), the co-ignimbrite tephra is deposited overlying the Plinian deposit forming strongly stratified deposits. At distances of 400–500 km from source there is still an identifiable Plinian deposit with a sharp contact before the overlying co-ignimbrite deposit. With further distance from source this contact becomes less defined as the tephra from the separate phases becomes increasingly mixed in the atmosphere (B2). At great distances (>1400 km) the tephra is completely mixed in the atmosphere and is transported downwind at velocities greater than the velocities of individual particles shown by similar grain size distributions over great areas (B3).
The physical characteristics of the CI tephra layer yield important information regarding tephra transport within the atmosphere, particularly at great distances from the source, which is difficult to study for smaller eruptions owing to preservation limitations.

The information, particularly thickness trends, preserved in deep sea deposits is shown to be equivalent, if not better, than that from subaerial locations. Thickness is shown to follow an exponential decrease in the medial to very distal reaches (400–1500 km). Both Plinian and co-ignimbrite contributions can be identified to downwind distances of 1400 km, with the Plinian fraction comprising 40 ± 5% of the deposit between 130 and 900 km. The Plinian component forms the coarse mode and the co-ignimbrite component the fine mode in bimodal deposits. Both modes follow exponential trends; the coarse mode decreases rapidly while the fine mode increases slightly with distance from source. At greater distances there is very little change in grain size distribution over hundreds of kilometres. This is inferred to represent the distal plume where spreading is controlled by ambient turbulence but is still at speeds greater than the terminal velocity of the particles allowing transportation of tephra over continental sized areas.

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Conclusions

This work comprises high-resolution, systematic analysis of tephra physical characteristics with distance from source for the CI eruption (39 kyr).
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