Bull Volcanol (1993) 55:343–356

Bulletin of Volcanology

The Neapolitan Yellow Tuff – A large volume multiphase eruption from Campi Flegrei, Southern Italy

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Received June 26, 1992/Accepted March 1, 1993

Abstract. The Neapolitan Yellow Tuff (NYT) (12 ka BP) is considered to be the product of a single eruption. Two different members (A and B) have been identified and can be correlated around the whole of Campi Flegrei. Member A is made up of at least 6 fall units including both ash and lapilli horizons. The basal stratified ash unit (A1) is interpreted to be a phreatoplinian fall deposit, since it shows a widespread dispersal (>1000 km^2) and a constant thickness over considerable topography. The absence of many lapilli fall units in proximal and medial areas testifies to the erosive power of the intervening pyroclastic surges. The overlying member B was formed by many pyroclastic flows, radially distributed around Campi Flegrei, that varied widely in their eruptive and emplacement mechanisms. In some of the most proximal exposures coarse scoria and lithic-rich deposits, sometimes welded, have been identified at the base of member B. Isopach and isopleth maps of fall-units, combined with the distribution of the coarse proximal facies, indicate that the eruptive vent was located in the NE area of Campi Flegrei. It is considered that the NYT eruption produced collapse of a caldera approximately 10 km diameter within Campi Flegrei. The caldera rim, located by geological and borehole evidence, is now largely buried by the products of more recent eruptions. Initiation of caldera collapse may have been contemporaneous with the start of the second phase (member B). It is suggested that there was a single vent throughout the eruption rather than the development of multiple or ring vents. Chemical data indicate that different levels of a zoned trachyte-phonolite magma chamber were tapped during the eruption. The minimum volume of the NYT is calculated to be about 50 km^3 (DRE), of which 35 km^3 (~70%) occurs within the caldera.

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Key words: Neapolitan Yellow Tuff – multiphase – phreatoplinian – phreatomagmatic – caldera formation – pyroclastic surge – trachyte.

Introduction

Campi Flegrei is a large volcanic complex, situated immediately west of Naples in southern Italy (Fig. 1), which has been the site of numerous explosive eruptions for the last 48000 years (Cassignol and Gillot 1982; Rosi and Sbrana 1987). The most important structure of this complex is a caldera that has been associated with the eruptions of either the Campanian Ignimbrite (Rosi and Sbrana 1987; Barberi et al. 1991) or the Neapolitan Yellow Tuff (Lirer et al. 1987). The Campanian Ignimbrite, dated between 25000 and 42000 ybp (Alessio et al. 1971, 1973, 1974), is considered by some authors (Rosi et al. 1983; Rosi and Sbrana 1987) to be erupted from Campi Flegrei. Other workers, however, suggest an origin to the north of Campi Flegrei (Barberi et al. 1978; Di Girolamo et al. 1984; Scandone et al. 1991).

The Neapolitan Yellow Tuff, dated at 12000 ybp (Alessio et al. 1971, 1973; Rosi and Sbrana 1987; Scandone et al. 1991), occurs as thick and widespread deposits on the periphery of Campi Flegrei and in the Campanian Plain (Di Girolamo et al. 1984; Rosi and Sbrana 1987). The origin of, and stratigraphic correlations between, 'Neapolitan Yellow Tuff' outcrops on the periphery of Campi Flegrei, and in the Campanian Plain are, however, controversial. Two different hypotheses have been proposed:

1. The products are the result of a unique eruption, labelled the Neapolitan Yellow Tuff eruption (Scherillo and Franco 1967; Lirer and Munno 1975; Di Girolamo et al. 1984; Lirer et al. 1987; Orsi and Scarpati 1989; Scarpati 1990; Orsi et al. 1991).
2. The products were emitted at significantly different times from several eruptive centres (Parascandola 1936; Rittmann et al. 1950; Capaldi et al. 1987) and are

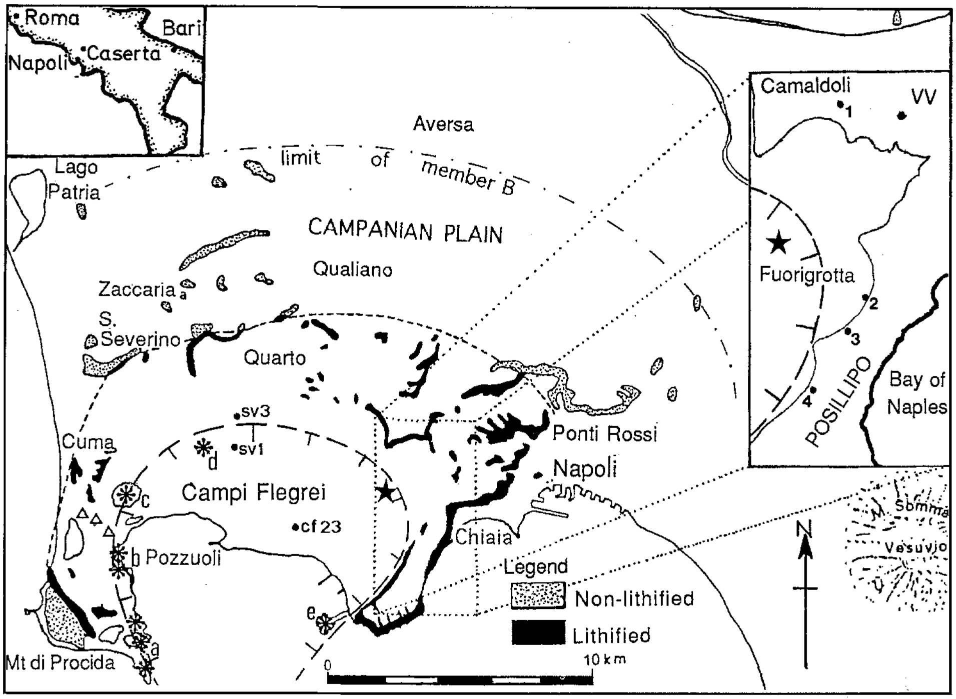

Fig. 1. Map showing the distribution of the NYT in and around Campi Flegrei. The *large broken line with ticks on the inside* shows the inferred boundary of the NYT caldera which relates in part to geophysical data of Lirer et al. (1987) and Scandone et al. (1991). The *dash-dotted line* indicates the extent of member B; the *broken line* depicts the transition from lithified to non-lithified facies and a *star* shows the presumed vent location. *sv 1 and 3*, San Vito boreholes; *open triangles*, Mofete boreholes; *cf 23*, Campi Flegrei 23 borehole. *Asterisks* indicate eruptive centers >8000 years old; *a*, Capo Miseno; *b*, Fondi di Baia; *c*, Archiaverno; *d*, Gauro; *e*, Nisida. Inset (right) shows the location of the proximal facies within the northeastern part of Campi Flegrei. *1*, Camaldoli, Soccavo face; *2*, Via Giulio Cesare; *3*, Via Coriolano; *4*, Via Cupa del Poligono; *VV*, Valle del Verdolino

grouped under the name 'Formation of the Neapolitan Yellow Tuffs' (Rosi and Sbrana 1987; Barberi et al. 1991).

We consider the Neapolitan Yellow Tuff (NYT) to be the product of a single eruptive event, thus consistent with hypothesis (1) above. Within the central part of Campi Flegrei, however, yellow tuff deposits occur associated with morphologically well-preserved tuff cones such as Gauro, Capo Miseno and Nisida occur (Fig. 1; Rittmann et al. 1950; Di Girolamo et al. 1984; Rosi and Sbrana 1987; Scandone et al. 1991). Many of these structures have been shown to be younger than 11000 ybp (Scandone et al. 1991) illustrating that they are unrelated to the older NYT. Furthermore, the largest of these, Gauro, has been considered by some workers (Scherillo and Franco 1967; Rosi and Sbrana 1987) to be the source of either all or part of the NYT. We consider this unlikely because the character of the base of the Gauro deposit differs from that of the NYT. Exposures of the Gauro deposit, 2km southwest of the rim, thin rapidly to only a few metres. The base consists of poorly sorted coarse pumice and ash layers that display large sand-wave structures, markedly different from layer A1 of the NYT, (see Figs. 2 and 3 for NYT).

The aim of this paper is to characterise the geological and volcanological nature of the NYT, as well as its geochemical variation. The stratigraphic and geochemical framework of this paper follows that of Orsi and Scarpati (1989) and Scarpati (1990) although the interpretation of several aspects of this work differs markedly from the recent work of Orsi et al. (1991). The study focuses on the physical volcanology of the first erupted products (member A), because of the presence of widespread marker-horizons that permit clear correlations between different outcrops. The field characteristics are described and the eruptive and emplacement mechanisms of the different layers in member A are discussed. The coarse proximal facies at the base of the overlying member B is also described (further details of member B are given in Cole and Scarpati 1993). Finally, we investigate the existence and location of a caldera related to the NYT eruption and estimate the volume of the erupted products.

The Geology of the Neapolitan Yellow Tuff

Stratigraphic correlation between different sections of the NYT at various localities, are shown in Fig. 2. A brown paleosol of variable thickness, from 15–20cm in Campi Flegrei, to 1m in the Campanian Plain, is always present at the base of the deposit. This paleosol has an average age of about 12000±500 ybp (Alessio et al. 1971, 1973; Rosi and Sbrana 1987; Scandone et al. 1991).

Within Naples itself (at Chiaia and Posillipo) and along the topographic border of Campi Flegrei (Monte di Procida, Cuma, S. Severino, NE of Quarto and Camaldoli, Fig. 1) the NYT always rests unconformably on older deposits. In the Campanian Plain, however, the contact of the NYT with underlying deposits is conformable.

The NYT consists mostly of pyroclastic-flow and minor fall deposits that occur as two different diagenetic facies: lithified and non-lithified (Scherillo 1955). The former has a yellow colour while the latter, the 'Pozzolana', is grey and preserves its primary depositional character. The lithification is the result of a diagenetic zeolitisation process (Norin 1955). The distribution of the lithified and non-lithified facies is shown in Fig. 1. Previous studies (Scherillo 1955; Di Girolamo

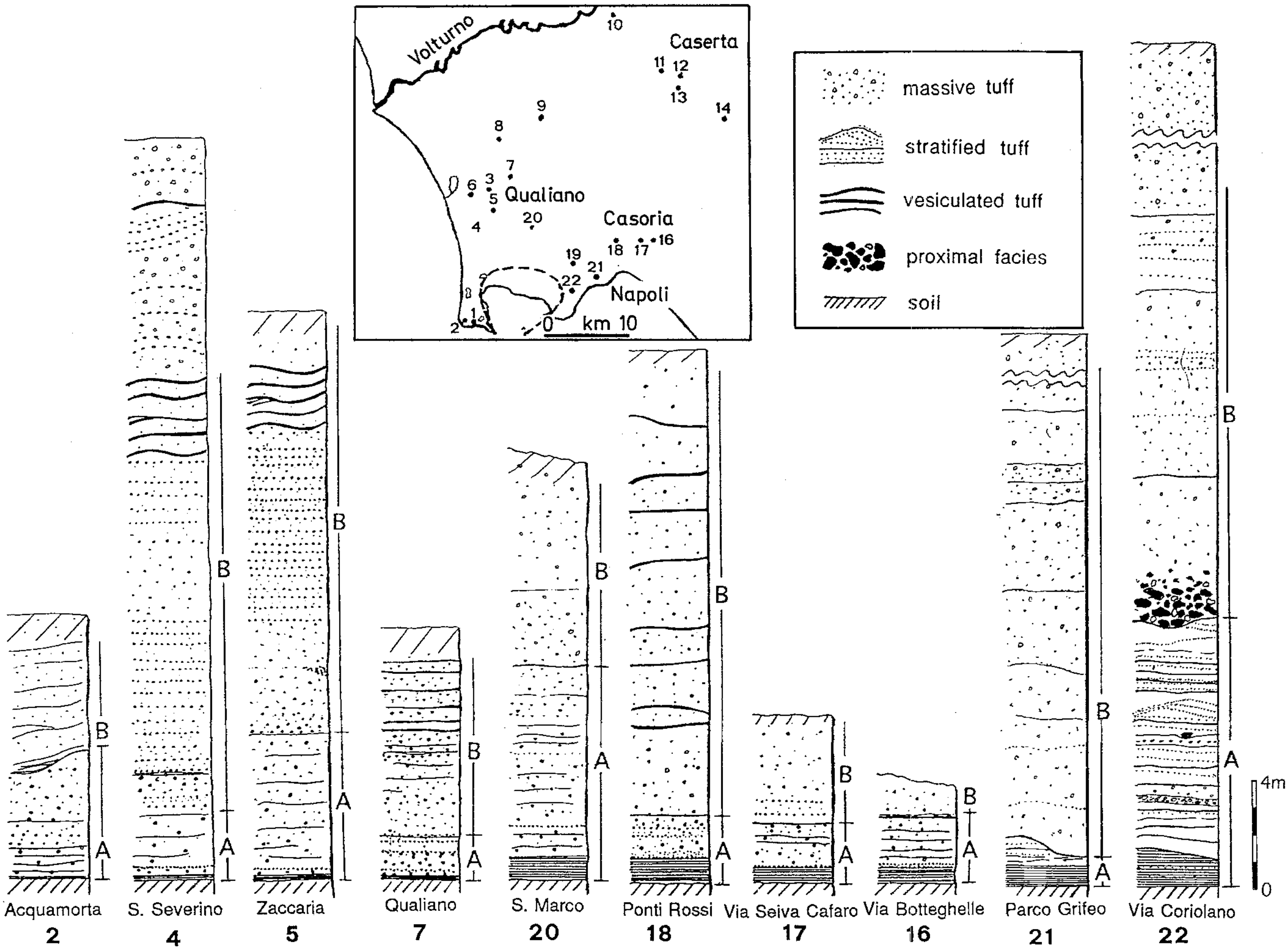

Fig. 2. Selected measured stratigraphic sections for the whole of the NYT. *A and B*, members A and B. Road names are given for locations within the city of Naples. The inset map indicates the location of NYT caldera and of all studied sections

1968), and observations made in the present study, show that the lateral transition between the two facies occurs gradually within tens or hundreds of metres.

Such lateral transitions between unlithified and lithified facies have previously been described from deposits exposed in saline alkaline lake environments (Hay 1978, 1986; Gottardi 1989), which are closed hydrological systems. de'Gennaro et al. (1990) recognised that the NYT is exposed within an open hydrological system. This is the only known formation to show such a transition in this environment.

This study includes examples from both the unlithified (pozzolana) facies and the more proximal lithified facies, although the details of sedimentary structures are obscured in the lithified facies. The maximum distance of NYT outcrops from the proposed vent is 31km. However, the most distal exposures of fall deposits have an average thickness of 1m, and it is likely that the NYT has a much wider distribution. This interpretation is supported by the presence of volcaniclastic material, dated at 12850±200 ybp, in a lacustrine sequence 110km north of Campi Flegrei (Frezzotti and Giraudi 1989) and by a trachytic ash layer (C-2), collected in deep-sea cores from the Tyrrhenian and Adriatic Seas, both of which are correlated with the NYT (Paterne et al. 1986, 1988).

Internal stratigraphy of the NYT

Two different members (A and B from bottom to top) have been distinguished on the basis of field characteristics and granulometric parameters, member A being generally finer grained than member B. Although member B rests erosively on member A in proximal areas there is no evidence of a significant time gap. These two members were also recognised by Orsi et al. (1991) who termed them lower and upper members. Each member is made up of numerous layers (Fig. 2).

Member A

Member A occurs throughout the studied area, being more widespread than member B. The thickness varies from 10m in proximal areas (section 22, Via Coriolano, Fig. 2) to about 1m in distal outcrops (sections 10, S. Angelo in Formis and 13, S. Marco Evangelista, Fig. 3).

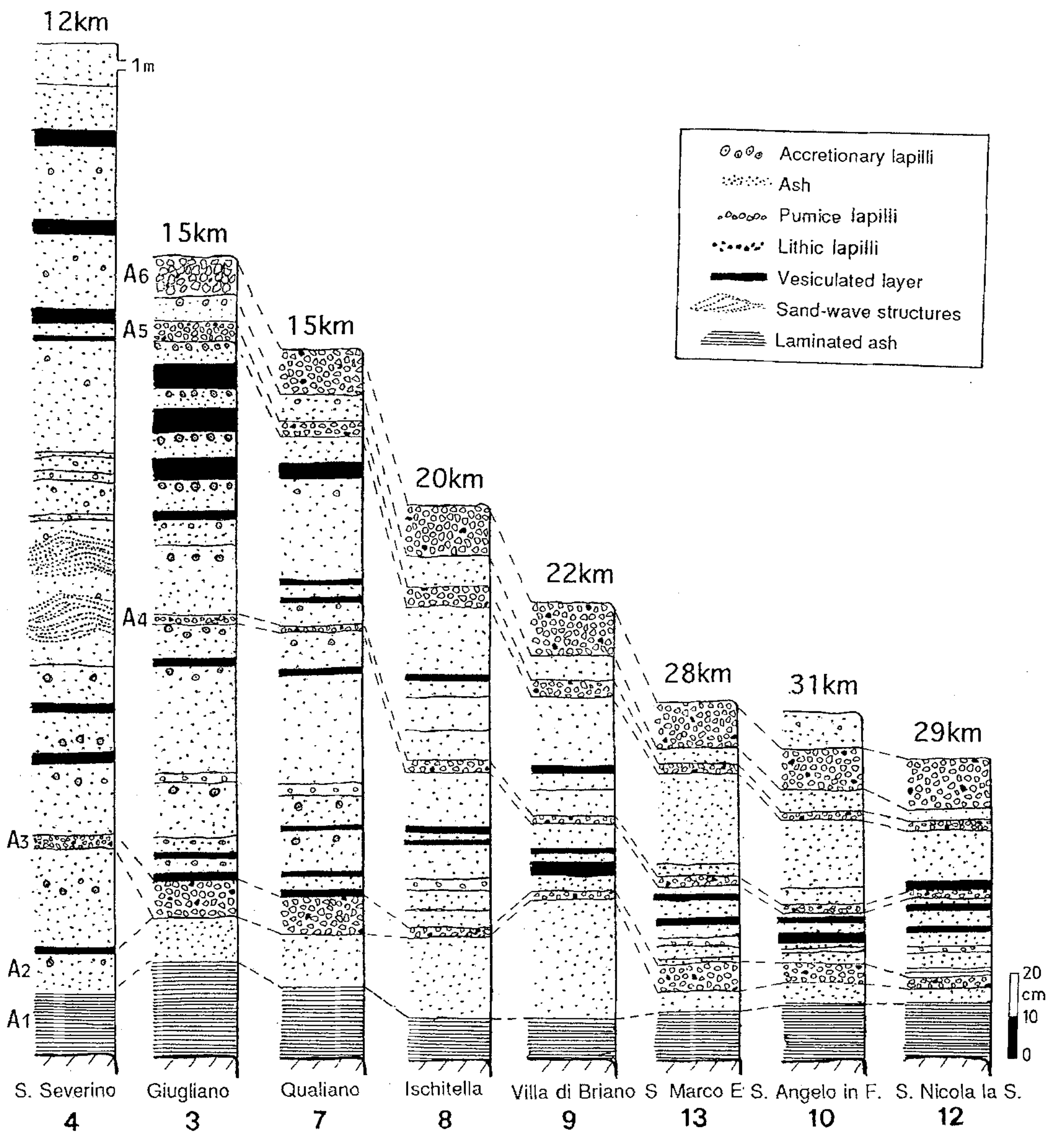

Fig. 3. Selected measured sections of member A, showing the detail of individual laminae. Locations as for Fig. 2. Distances at top of columns are measured from the presumed vent location

It is made up of at least six fall units (A1–A6 from base to top; Fig. 3), interbedded with numerous ash layers, for which there is abundant evidence for a pyroclastic surge origin up to a distance of 12km from the vent.

Unit A1

A1 is distinctive and readily identifiable, even in the most distal exposures, forming a useful marker horizon. It is well stratified consisting of up to 25 fine-ash layers, grey to pink in colour (Fig. 4). Its maximum thickness is 2.1m at Camaldoli, 2km from the presumed vent. The thickness of individual ash layers is as much as 40cm, but usually does not exceed 5cm, with an average thickness of 0.5–1cm. This unit is consistently fine grained even at the most proximal exposures. The principal components are pumice, glass shards, fragments of feldspars, mica and lithic clasts which do not exceed 1mm in diameter. In proximal outcrops (e.g. Ponti Rossi, Fig. 4) two well-sorted, fine lapilli horizons are intercalated within the ash layers. Accretionary lapilli are concentrated in some layers, especially in proximal sections, whereas others contain many small vesicles.

In some outcrops the ash-layers are interbedded with discontinuous lenses of reworked material of both volcanic and sedimentary (limestone clasts) origin. The thickness of the lenses varies between millimetres and decimetres. Similar horizons of reworked material also occur between other units of member A.

Small gullies occur locally. These are 5cm deep and 10cm wide with asymmetrical and stepped profiles. The layers filling these gullies are sometimes discontinuous; otherwise they retain a constant thickness from gully edge to centre. Similar gullies have been found in

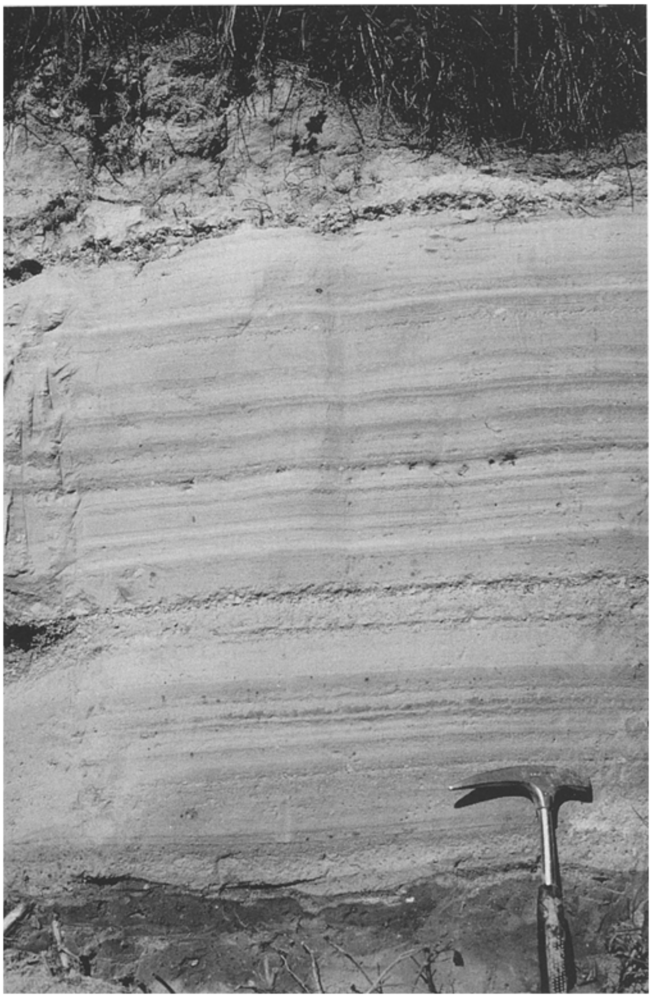

Fig. 4. Unit A1 of member A at Ponti Rossi (section 18 on Fig. 2). At this relatively proximal exposure A1 is 90 cm thick and is composed of many layers. Note the two coarser layers occurring approximately halfway above the base. Hammer head is 18 cm across

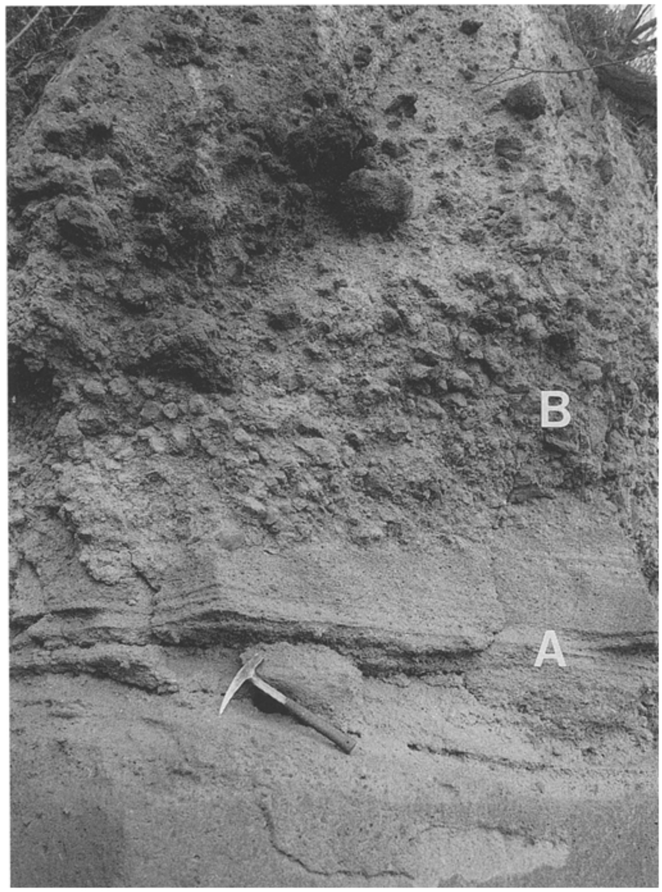

Fig. 5. The coarse proximal facies at the base of member B exposed in Via Coriolano on the Fuorigrotta face of Posillipo hill. Note coarse scoria and lithic blocks and the erosive contact with the underlying member A

deposits considered to have a phreatoplinian origin, for example the Ordovician Whorneyside Tuff in the English Lake district (Branney 1991), for which variations in thickness in layers filling the small gullies were attributed to post depositional rolling and grain flow, rather than to a surge origin. Therefore we consider that the filling of these small gullies by both continuous and discontinuous layers is consistent with a fall origin.

Unit A1 also commonly shows many soft sediment deformation structures, including:

1. load lobes and flame structures at the interface between two layers with different grain-size parameters (Dzulynski and Kotlarczyk 1962);
2. syn-depositional normal faults, with dislocations of a few centimetres. These could be formed by irregular shrinkage during consolidation immediately after deposition of individual layers similar to that described by Potter and Pettijohn (1963);
3. diapirs that penetrate into overlying units;
4. convolutions, occasionally accompanied by faint and small-scale cross-bedding. The cross-bedding occurs over horizontal distances of <10cm. On the basis of this small-scale cross-bedding Orsi et al. (1991) interpreted unit A1 (which they refer to as LM1), as a pyroclastic surge deposit. This type of small-scale structure could be formed by at least four different secondary processes: local slumping as described by Walker (1981) for small-scale cross-bedding structures, that resemble those described here, within phreatoplinian fall deposits from New Zealand, which would be especially well developed in deposits on steep paleoslopes; fluvial reworking possibly induced by rainstorms that are likely during phreatomagmatic eruptions; reworking by local winds also contemporaneous with the eruption; and grainflow of unconsolidated ash down steep paleoslopes and into intraformational gullies. Furthermore these small-scale cross-laminations differ markedly from those in unambiguous pyroclastic surge deposits, at higher levels within members A and B, that possess large wavelength (up to 14m) sandwave structures. Such a large wavelength would be expected in the deposits of a pyroclastic surge that travelled at least 35km (the maximum distance of A1 from source).

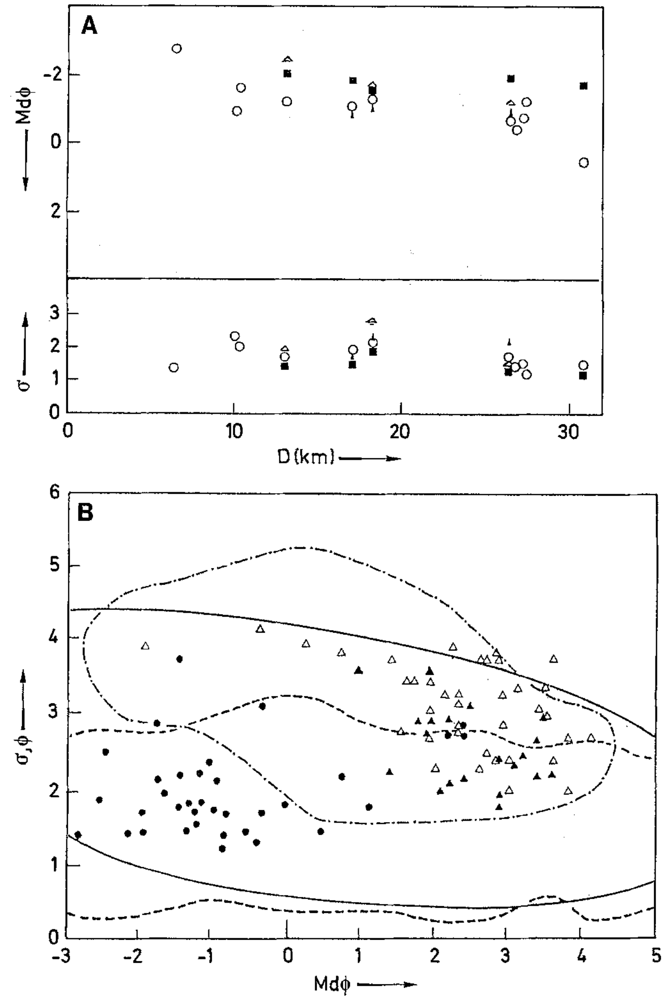

Fig. 6. A (upper) – Mdø versus distance for pumice lapilli layers A3, A4, A5, A6. (lower) Sorting versus distance for pumice lapilli layers. **B** Mdø versus sorting for both members A and B. The *solid line* indicates pyroclastic surge field (Fisher and Schmincke 1984), *broken line* the fallout field and *dotted and dashed line* is the pyroclastic flow field of Walker (1971). *Solid symbols* data from Scarpati (1990) and *open symbols* data from Cole and Scarpati (1993)

Unit A1, in fact, shows remarkable laterally continuous, plane-parallel stratification recognised in both proximal and distal exposures. In addition its thickness remains almost constant over the considerable topography that forms the border of Campi Flegrei. This, coupled with the regular decrease in thickness of A1 with distance from Campi Flegrei and the lack of discernible lateral variation in facies for tens of kilometres, strongly suggest a fall origin for the unit.

Unit A2 and fine ash layers

The remainder of member A is formed by fine-grained ash layers interbedded with pumice lapilli fall units (A3, A4, A5 and A6). Unit A2 is an accretionary lapilli-bearing ash layer that can be confidently correlated between all distal exposures. It retains a constant thickness even within proximal areas and is therefore interpreted as a fall deposit.

The other ash layers consist of alternating vesicular and accretionary lapilli-bearing intervals (Fig. 3) and are composed mainly of ash-grade material with scarce pumice and lithic lapilli. The accretionary lapilli, are more abundant in proximal areas, and occur concentrated in aggregates or horizons commonly near the tops of these layers; some show signs of flattening, with the longest axes lying horizontally.

The thickness of some accretionary lapilli-bearing layers, especially within proximal areas, is strongly controlled by local topography with significant accumulations in topographic lows. The layers often display planar bedding or sand-wave structures with wavelengths of 6–14m and amplitudes of 0.5–1m. Cross-bedding is also occasionally observed and contacts between layers are commonly erosional.

The presence of sand-wave structures, cross-bedding and thickening within topographic lows of many accretionary lapilli-bearing ash layers indicate that they were deposited from dilute turbulent pyroclastic surge clouds (Cas and Wright 1987). The absence or thin nature of the pumice lapilli fall layers (A3, A4, A5, A6) within the most proximal exposures may be attributed to erosion by these pyroclastic surges.

The vesicular layers, with which the accretionary lapilli layers are associated, show constant thickness and mantle preexisting topography. They are therefore considered to be fall deposits.

Units A3, A4, A5, A6

These units are thin, massive and well-sorted pumice lapilli layers (Fig. 3) with maximum thicknesses of 9, 3, 4 and 12cm respectively. The maximum thicknesses occur in sites at 5–7km north of Campi Flegrei. Many of these layers gradually thin and become coarser toward proximal sections where they may be entirely absent (compare proximal San Severino with more distal sections in Fig. 3) due to erosion by subsequent pyroclastic surges. They are composed of grey, subangular pumice lapilli with subordinate lithic fragments, typically subangular grey trachytic lavas or green tuffs. The units also show a wide dispersal and mantle bedding, and are interpreted to be fall deposits produced by a purely magmatic 'dry phase' of the eruption.

Member B and the proximal facies

Member B is found up to 14km from the vent (Fig. 1). As described in detail by Cole and Scarpati (1993), member B is composed of numerous layers and has both a lithified (in more proximal regions) and an unlithified facies. In general, it can be distinguished from member A by its coarser grain-size and by the presence of thicker massive units, often several metres thick in its lower part. Maximum thicknesses for the non-lithified and lithified facies are 20–25m and more

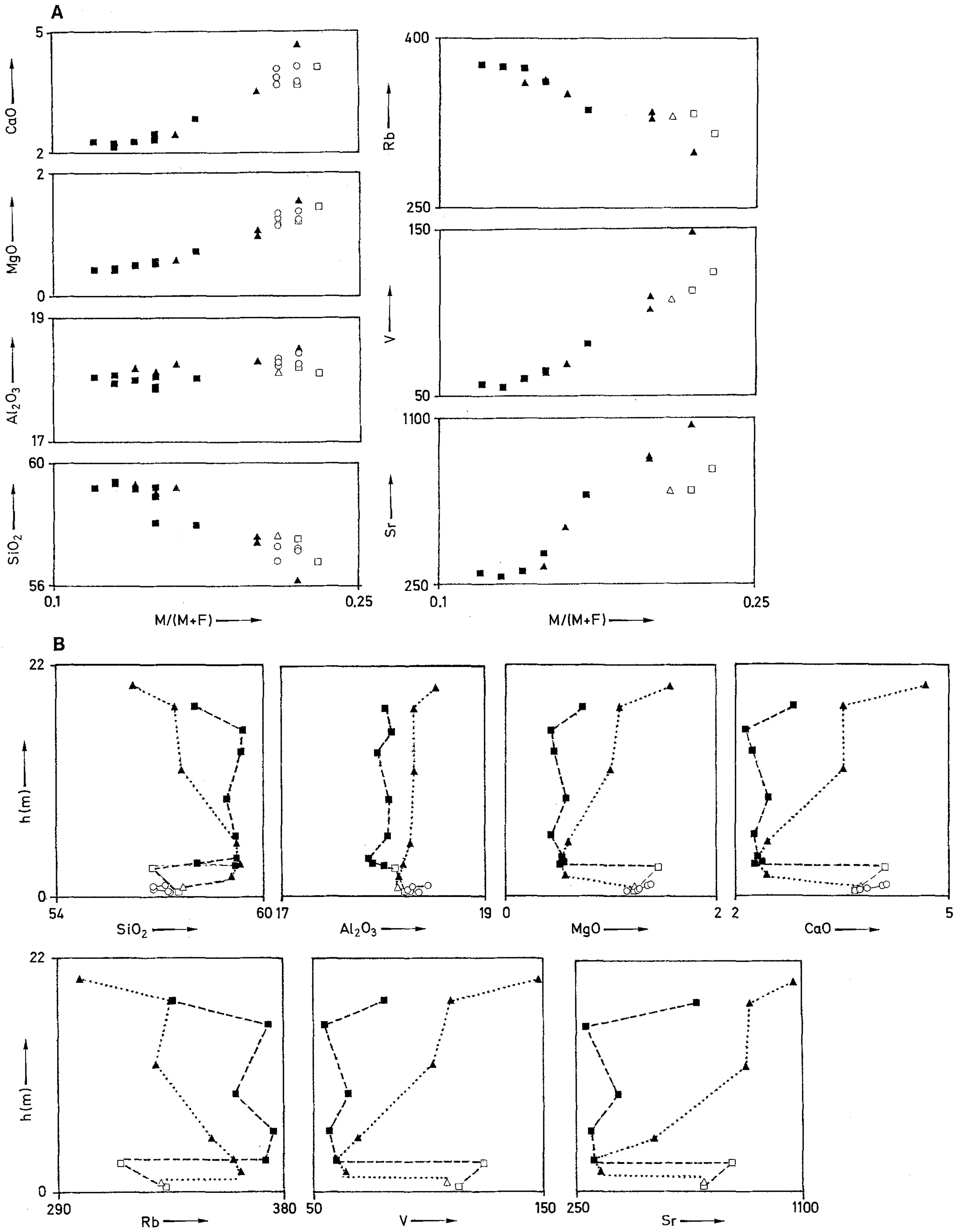

Fig. 7. A Variation of major and trace elements vs $MgO/(Fe_2O_3 + MgO)$. **B** Variation of major and trace elements with stratigraphic height. *Triangles*, Ponti Rossi; *squares*, San Severino; *circles*, S. Angelo in Formis; *open symbols*, member A; *closed symbols*, member B

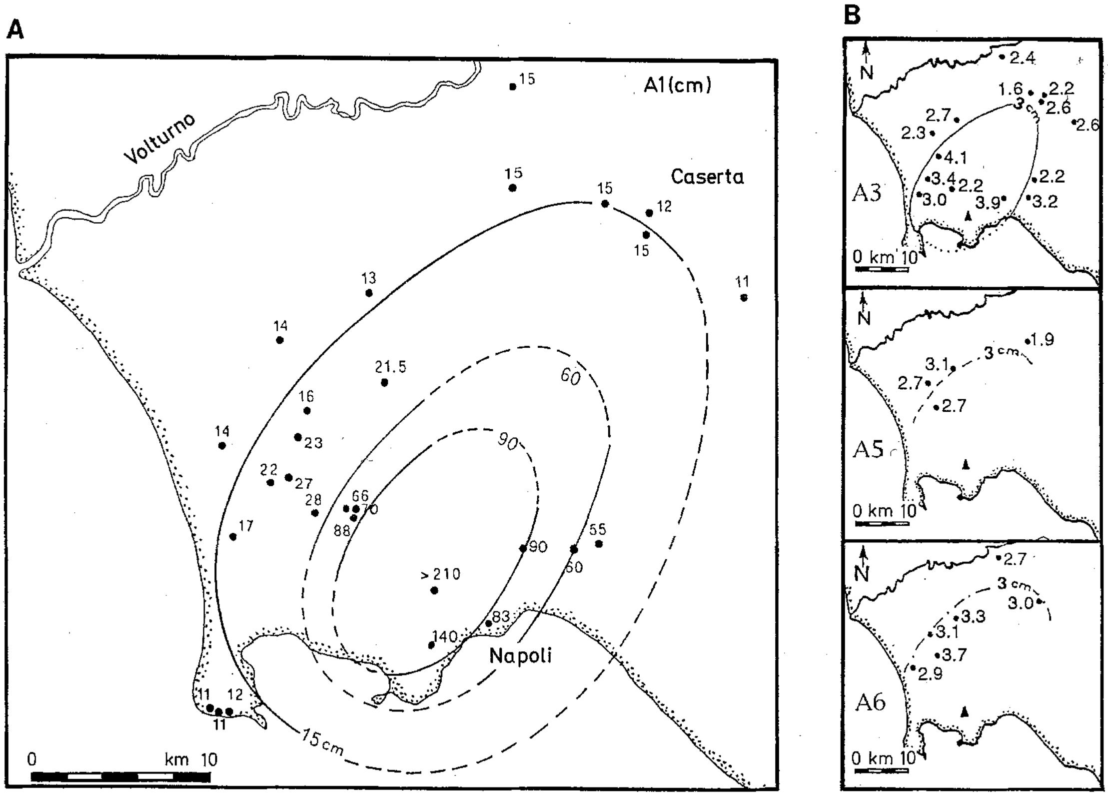

Fig. 8. **A** Isopach map of unit A1. Thicknesses are given in centimetres. Note dispersal axis to the northeast. **B** Isopleth maps of the 3cm diameter pumice clasts from pumice lapilli layers A3, A5 and A6. The locations showing the average largest pumice clasts for units A3, A5 and A6. The average is calculated from the five largest clasts from any one exposure

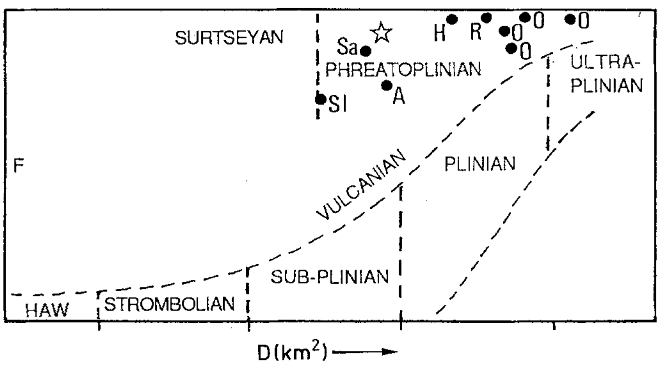

Fig. 9. Classification of explosive eruptions after Walker (1973) and Self and Sparks (1978). The *star* represents the unit A1 that falls within the phreatoplinian field. Also shown are representative phreatoplinian eruptions from the literature: *A*, Askja 1875; *H*, Hatepe; *O*, Oruanui members; *R*, Rotongaio Ash; *Sa*, Sete A; *Sl*, Sete L (after Self and Sparks 1978; Walker 1981). *D* is the area enclosed by the isopach for which the thickness is 1/100 of the maximum thickness (T_{max}); *F* is the percentage of <1mm particles in the deposit on the dispersal axis where it crosses the 0.1 T_{max} isopach

than 60m respectively. In contrast to member A, the component layers range in thickness from centimetres to metres. Several different lithofacies have been identified within member B, including massive lapilli tuffs, of which there are two types: stratified and sand-wave facies for which water probably only played a minor role. In addition accretionary lapilli-bearing and vesicular ash facies (Fig. 2) are recognised that were probably phreatomagmatic. Complex associations between the various lithofacies are recognised. In summary member B was formed by numerous pyroclastic flows that varied widely in style. A detailed analysis of the different lithofacies within member B is given in the companion paper (Cole and Scarpati 1993).

At four proximal locations within the east and northeastern part of Campi Flegrei, there is a distinctive facies that has been identified that is always situated at the base of member B. This facies is particularly coarse and occurs as both welded and non-welded facies.

Two welded exposures have been identified. At Camaldoli, on the Soccavo face (Loc. 1, Fig. 1), an intensely welded layer, 2.5m thick, occurs within a ~4m wide channel cut into the underlying member A. The welded part includes clasts up to 1m in size, and grades upwards into the massive, finer-grained, yellow tuff of member B. Secondly, in Fuorigrotta, on via Giulio Cesare (Loc. 2, Fig. 1), a lensoid welded layer, up to 4m thick and 15m wide, occurs at the base of member B. Scoria clasts in Fuorigrotta are up to 50cm in size, welding is less intense than at Camaldoli, and in places a fines-poor matrix may be identified.

The non-welded facies has been identified at two locations on the Fuorigrotta face of Posillipo Hill. At Via Coriolano (Loc. 3, Fig. 1) this facies consists of abundant, poorly vesicular magmatic scoria and accessory lithic blocks up to 65cm across, although more commonly 30–40cm in size, set in a fines-poor matrix. Several lithic types are present including green and yellow tuff, hydrothermally altered and lava clasts. This coarse facies also rests on an erosional surface cut into member A (Fig. 5). At Via Cupa del Poligono (Loc. 4, Fig. 1), discontinuous lenses of coarse scoria and lithic lapilli frequently ~30cm in size, similar to those in Via Coriolano, occur within a ~6m thick, fines-poor unit. We consider that the coarse, occasionally welded and sometimes fines-poor nature of this facies is a function of proximity to the vent. Both the welded and nonwelded facies were emplaced by a pyroclastic flow that eroded the underlying member A. This erosion, coupled with the sometimes fines-poor nature of this proximal facies, suggests that this flow was well inflated/fluidised (Cas and Wright 1987).

Granulometric and morphometric analysis

Granulometric analyses of member A pumice lapilli layers and member B were made by mechanical sieving ($< +4\ \phi$) and Coulter counter ($> +4\ \phi$) (Allen 1981). None of the ash-rich layers in member A were analysed because of the strong aggregation of particles that resisted either light acid or ultrasonic treatment.

Airfall lapilli layers A3 and A5 show a decrease in Mdϕ ($=\phi50$) with distance from 5 to 30km (Fig. 6a). Sorting ($\sigma\phi=(\phi84-\phi16)/2$) (Inman 1952) seems to have been unaffected by the distance of 30km (Fig. 6b), as is usually the case for plinian fall deposits (Self and Sparks 1978).

On the Mdϕ versus σ diagram (Fig. 6b) sample points overlap the fields for pyroclastic flow, surge and fall deposits. The points for members A and B, however, fall in distinctive fields. Member A is better sorted and has a higher Mdϕ than member B. Also the member A lapilli deposits are nearly all restricted to the fall field of Walker (1971), consistent with the field interpretation, whereas all the analysed member B deposits plot within the pyroclastic flow field.

Several samples were collected at different stratigraphic levels within member A for SEM morphometric analysis. Samples from the ash-rich layers possess clasts with a low vesicularity and planar or curviplanar surfaces with blocky shapes. The vesicles are filled with fragments adhering to the walls. Alteration occurs as hydration (increasing the roughness of edges) or by secondary mineralisation (causing smoothing of corners). In contrast the pumice layers have pumiceous shards possessing flat surfaces with round or tubular vesicles with no filling.

Overall, the shape of pyroclasts in the ash layers of member A are similar to those produced by hydromagmatic eruptions (Heiken 1972, 1974; Heiken and Wohletz 1985), whereas those of the pumice layers are typical of purely magmatic eruptions (Heiken and Wohletz 1985).

Petrology and geochemistry

Fresh composite pumice samples representative of the whole NYT succession were collected at various stratigraphic heights and from different locations. Typical major and trace element analyses from the Ponti Rossi section are given in Table 1.

The samples range in composition from trachytes to phonolites (classification according to Le Bas et al. 1986) and are characterised by rare phenocrysts and microphenocrysts of sanidine, with minor amounts of plagioclase, greenish pyroxene, biotite and apatite in a glassy groundmass. The phases sometimes occur also as glomeroporphyritic clusters.

Oxides SiO_2 and K_2O increase with decreasing $MgO/(Fe_2O_3+MgO)$, while CaO, MgO and TiO_2 decrease (examples shown in Fig. 7a). Al_2O_3 shows an almost constant value, compatible with fractionation dominated by the removal of alkali feldspar (Fig. 7a).

The trace elements Zr, Nb, Th, Rb and Y show a markedly incompatible behaviour, whereas V, Sc, Sr and Ba all decrease with differentiation (examples of these trends are shown in Fig. 7a). Although there are well-defined chemical trends, the data fall into two distinct groups separated by a compositional gap. The presence of this compositional break at both San Severino ~12km west of the probable vent and Ponti Rossi ~8km northeast, suggests that the gap is real. We infer that immediately prior to the eruption the magma chamber was compositionally zoned with an upper layer of phonolite and a lower layer of less evolved trachyte. Orsi et al. (1991) observed a similar chemical trend through the sequence. They interpreted the variation to be derived from two parental magmas. An alternative explanation is that the zonation was the product of crystal fractionation of the observed mineral phases from a single mafic trachytic magma. The interpretation of a single parent magma for the NYT is supported by the remarkably constant $^{87}Sr/^{86}Sr$ ratios (0.70747–0.70763) (Table 1).

The analyses are plotted against stratigraphic height in three selected sections (Fig. 7b). For the more proximal sections, which include member B, the least differentiated samples plot at the base and top and the most salic trachytes plot in the middle. It may be noted that the composition of samples from member A is very similar but changes to markedly more evolved compositions at the base of member B. Within the uppermost part of member B the magma composition becomes less evolved once more. Such a variation suggests that the magma chamber had become compositionally zoned before the eruption. Initially less differentiated magma was erupted from lower levels in the magma chamber. This was followed by eruption of more evolved magma and finally evacuation of less evolved magma again.

Table 1. Representative major (XRF), trace elements (ICP), $^{87}Sr/^{86}Sr$ ratios and CIPW norms of pumice clasts through the NYT at Ponti Rossi (Fig. 2). Samples are from 63 A at the base to 75B at the top of the sequence and correspond to each sample in Fig. 7b. (A) or (B) indicates respective member. Total Fe is expressed as Fe_2O_3; L.O.I. loss on ignition. Oxides are in wt%, trace elements in ppm. Sr-isotope composition is measured on K-feldspar separates. $^{87}Sr/^{86}Sr$ $2s = \pm 1 \times 10^{-5}$. The complete set of analyses is available upon request to the senior author

Sample	63 (A)	65 (A)	67 (B)	68 (B)	72 (B)	74 (B)	75 (B)
SiO_2	57.66	59.06	59.33	59.22	57.62	57.43	56.20
TiO_2	0.46	0.40	0.38	0.35	0.41	0.44	0.59
Al_2O_3	18.13	18.14	18.19	18.26	18.30	18.30	18.51
Fe_2O_3	4.98	3.54	3.41	3.50	4.41	4.85	6.06
MnO	0.14	0.14	0.15	0.12	0.13	0.13	0.14
MgO	1.22	0.56	0.51	0.59	0.99	1.08	1.56
CaO	3.76	2.44	2.28	2.46	3.52	3.52	4.67
Na_2O	3.89	4.47	4.57	4.07	3.62	3.64	3.38
K_2O	7.82	8.03	7.92	8.36	8.26	8.10	7.70
P_2O_5	0.14	0.12	0.12	0.13	0.26	0.22	0.34
L.O.I.	1.78	3.26	3.31	3.06	2.59	2.40	0.94
Total	99.98	100.16	100.17	100.12	100.11	100.11	100.09
M/(F+M)	0.21	0.15	0.14	0.16	0.20	0.20	0.22
Ba	1237	274	207	555	1851	1780	2109
Cu	11	7	6	5	9	8	16
Nb	31	40	42	31	26	26	22
Ni	6	6	5	6	7	5	8
Rb	331	336	360	351	329	335	299
Sc	6	3	3	3	5	5	8
Sr	728	343	317	544	889	904	1068
Th	25	31	32	26	23	23	22
V	108	64	60	69	102	110	148
Y	30	32	32	28	27	28	27
Zn	79	76	75	71	72	71	75
Zr	288	340	341	286	258	262	241
$^{87}Sr/^{86}Sr$	0.70754	0.70753	0.70747	0.70759	0.70763	0.70757	0.70759

The NYT caldera

The lack of proximal outcrops of NYT, together with other geological and borehole evidence (discussed below) indicate that caldera formation was associated with this eruption (Fig. 1). The topographic border of Campi Flegrei that has been interpreted as the caldera rim of either the Campanian Ignimbrite (Rosi and Sbrana 1987; Barberi et al. 1991) or the NYT (Lirer et al. 1987) is in fact mantled by tuffs that underlie the NYT, for example the Whitish Tuffs at Camaldoli, dated at about 16000 ybp (Alessio et al. 1973). Therefore the NYT is not related to any structure located on the topographic boundary of Campi Flegrei. This is further supported by the fact that stratified lapilli fall layers occur beneath the NYT but overly the unconformity east of Quarto. We consider that the rim of the NYT caldera occurs within the topographic border of Campi Flegrei (Fig. 1). Borehole data (D' Erasmo 1931) reveals at least 200m of yellow tuff (most probably NYT) in the Fuorigrotta plain, suggesting major displacement between Posillipo hill and Fuorigrotta. Thus we suggest that the Fuorigrotta face of Posillipo hill approximates the southeastern border of the NYT caldera (see Fig. 1). Elsewhere the caldera rim is presently buried by the products of younger eruptions. Nevertheless, further information on the position of the caldera rim can be gained from the San Vito (SV 1 and 3) and Mofete boreholes described by Rosi and Sbrana (1987) and Barberi et al. (1991). From SV 3 to SV 1, the NYT increases in thickness from 150m to 500m. In addition, the base of the NYT is ~600m lower in SV 1 than in SV 3, a difference which we interpret as due to downfaulting. These data therefore strongly suggest that a major caldera fault related to the NYT exists between the San Vito boreholes. A somewhat constant thickness of ~200m of NYT in the Mofete boreholes (Fig. 1, Barberi et al. 1991) near the western border of Campi Flegrei further suggests that the caldera fault is located to the east of these boreholes. These data give an approximate caldera diameter of 10km (Fig. 1). The presence of a caldera associated with the NYT is supported by the presence of a negative geophysical anomaly described by Scandone et al. (1991). The location of the caldera shown in Fig. 1 largely coincides with this geophysical anomaly.

The location of several eruptive centres (e.g. Capo Miseno, Fondi di Baia, ArchiAverno, Gauro and possibly Nisida; Fig. 1) that postdate the NYT with an age of >8000 years may approximate the position of the NYT caldera rim. The caldera fault may have provided a weakness that was exploited by later activity, as envisaged by Scandone et al. (1991).

Distribution and volume of the NYT

A sufficient number of outcrops were identified to reconstruct an isopach map for unit A1 and isopleth maps for units A3, A5 and A6 (Figs. 8a, b). Isopachs of unit A1 demonstrate the sheet-like form of the deposit and show a NE-trending dispersal axis (Fig. 8a). Their regular distribution also suggests that deposition was not influenced by local rainstorms (Self 1983) and, hence, that the water responsible for producing accretionary lapilli was an inherent component of the eruption column, and perhaps derived from a lake or other shallow-water environment at the vent. Moreover, the widespread dispersal (Fig. 9) and fine grain-size of A1 suggest that it is the deposit from a phreatoplinian eruption.

The variation in thickness of unit A1 further indicates a source in the northeastern part of Campi Flegrei. Such a location would also be consistent with the isopleth distributions of units A3, A5, and A6 (Fig. 8b) and with the proximal facies found at the base of member B in this area. In addition bomb sags found on the Soccavo face of Camaldoli within member A, suggest a source within Fuorigrotta (Fig. 1).

The maximum distance of member B is approximately 14km from the inferred source area. It has a radial distribution around Campi Flegrei and covers an area of about 325km^2 on land.

Some constraint on the intracaldera volume can be gained from borehol data. The borehol San Vito 1 (Rosi and Sbrana 1987), located just inside the caldera, reveals a 500m thickness of NYT (Barberi et al. 1991). A more centrally located borehole (CF23, Fig. 1) has revealed 850m of tuff (Minucci 1964) which Scandone et al. (1991) interpret as NYT. We therefore assume a thickness of 500m of NYT at the edge of the caldera increasing to 850m toward its centre. Furthermore, borehole evidence (Mofete wells and San Vito 3) also show that a significant thickness of NYT occurs outside the caldera but within Campi Flegrei, probably due to accumulation within local topographic depressions.

The thicknesses and dimensions of the various parts of the NYT and their resulting volumes are presented in Fig. 10. The total dense rock equivalent volume for the NYT is 49.3km^3 and an original magma volume of 45.6km^3 DRE. However this estimate is probably only a minimum volume since the co-ignimbrite ash has not been taken into account. It should be noted that from this volume estimation ~70% of the NYT has accumulated within the caldera. Similar ratios for intra and extracaldera volumes have been recorded for the Bishop Tuff at the Long Valley caldera where 350km^3 of a total of 500km^3 has accumulated within the caldera (Bailey et al. 1976). Also in the San Juan Mountains, Colorado at the Lake City caldera, the intracaldera ash flow is 1.5km thick whereas the outflow tuff is <100m thick (Lipman 1976). The large intracaldera volume estimated here for the NYT is probably the reason for the smaller volumes given by other authors e.g. Lirer et al. (1987) — 20–30km^3 DRE; Barberi et al (1991) — 10km^3 DRE; Orsi et al. (1991) — 20km^3 DRE.

NYT	volume (km^3)
A1 [1]	1.2
ash and lapilli fall deposits of member A	4
flow and surge deposits of member A and B [2]	14.4
local buried accumulations within Campi Flegrei	3.8
intracaldera	55.7
total	79
total (DRE) [3]	49.3
lithics [4]	3.7
magma	45.6

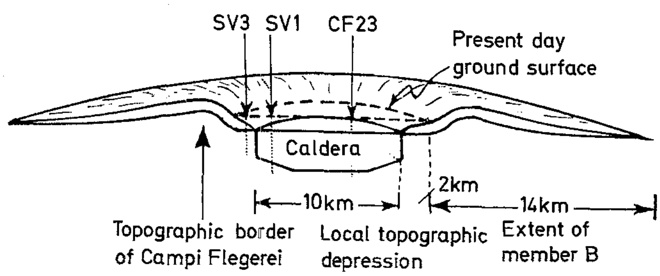

Fig. 10. Schematic diagram showing dimensions of the various parts of the NYT used in volume estimations. The table shows volume estimations for the NYT. Techniques used are: (1) calculated using the method of Pyle (1989); (2) assume an original radial volume. The actual outcropping (on land) volume is 7.2 km^3; (3) magma density = 2.4 g/cm^3, tuff density = 1.5 g/cm^3; (4) calculated from component analyses of member B in Cole and Scarpati (1993)

Discussion

Member A is characterised by multiple ash layers that are rich in fine ash in both proximal and distal areas. The presence of accretionary and armoured lapilli and plastic deformation structures all indicate deposition from an eruption column rich in water vapour, and probably phreatomagmatic in origin (e.g. Self and Sparks 1978; Sparks et al. 1981; Walker 1981; Self 1983; McPhie 1986; Branney 1991). The shapes of juvenile pyroclasts from member A are also consistent with an eruption influenced by water/magma interaction. The basal unit A1 has a dispersal and fragmentation similar to phreatoplinian fall deposits (Fig. 9). The calculated volume for unit A1 of ~0.7km^3 DRE is also comparable to those for other phreatoplinian ashfall deposits. For example, the volumes of the Hatepe and Rotongaio ashes of the Taupo eruption (New Zealand) are 1.02 and 0.73km^3 DRE respectively (Walker 1981), while that of Layer C of the 1875 Askja tephra deposits is 0.17km^3 (Self and Sparks 1978). We therefore consider that unit A1 was derived from phreatoplinian activity. To our knowledge this is the first documented example of a phreatoplinian eruption involving trachytic products, all others so far reported being rhyolitic or dacitic. The pumice lapilli beds, their coarse grain-size and morphometric features, suggest periodic 'dry' magmatic activity during an otherwise dominantly phreatomagmatic phase. Similar fluctuations between phreatoplinian and plinian (wet-dry) activity have been recognised in other explosive eruptions for example the Taupo 186 AD eruption in New Zealand (Walker 1981).

In member A sand-wave bedded pyroclastic surge deposits are abundant in proximal locations. During transport these surges eroded the underlying deposits up to ~12km from the vent. As a result of this erosion some of the lapilli-fall layers, found in the distal regions, are not present in more proximal exposures.

At distances greater than 12km from the vent evidence for a pyroclastic surge origin for the accretionary lapilli-bearing layers, such as cross-stratification, sand-wave structures and lateral thickness variations, are extremely rare. For these reasons it has been difficult if not impossible to assign a genetic origin to these layers within more distal regions. Besides, in distal regions the processes taking place within a phreatomagmatic surge cloud will include the settling of ash with only slight lateral movement. This seems likely as sedimentation of large quantities of ash will cause 'lofting' and deceleration of the surge cloud.

The chemical data show that the initial part (member A) and the final stages of the eruption tapped less-evolved magma than that tapped by the middle phase. The likely position of the vent, as previously discussed, is within the northeastern part of Campi Flegrei. If the rim of the proposed caldera approximates the extent of the magma chamber then the vent is likely to have been located at the margin of the magma chamber. It is thus possible that initially a lower, less-evolved, part of the magma chamber was tapped. The change from member A, containing lapilli-fall layers, to member B, composed entirely of thick pyroclastic flow deposits and a basal coarse proximal facies, suggests an increase in mass discharge rate with time. This increase in discharge rate could cause tapping of magma from a higher and more differentiated level; a waning discharge rate towards the end of the eruption may have again tapped less-evolved magma from lower levels. This scenario is similar to that proposed by Gardner et al. (1991) for the plinian phase of the Bishop Tuff.

In summary, from the results of stratigraphic, field and laboratory studies of the erupted products we propose the following course of events during emplacement of the NYT.

The eruption probably occurred within a shallow water environment with the formation of a phreatoplinian eruption column. This involved numerous explosions that gave rise to the initial laminated ash-fall unit A1 (Fig. 11a). Fluvially reworked material at several levels, both within unit A1 and generally within member A, suggests that there were at least short time gaps between separate pulses of this phase. Pyroclastic surges that formed deposits within the upper part of member A could have been derived either from partial collapses of the phreatoplinian eruption column or directly from the vent (Fig. 11b). This phreatomagmatic activity was punctuated by at least four brief 'dry' magmatic phases which produced the pumice lapilli-fall layers. The formation of the coarse proximal facies during the first part of member B may indicate the onset of caldera collapse related to a dramatic increase in discharge rate. Repeated eruption column collapse generated the numerous pyroclastic flows which produced member B (Fig. 11c). The presence of accretionary lapilli and vesicular ash layers at intervals within member B indicate at least periodic phreatomagmatic activity during this phase. The large intracaldera thickness of NYT indicates that caldera collapse may have continued throughout the eruption of member B in an incremental fashion. The ability to correlate distinctive layers within member B (Cole and Scarpati 1993) and the similarity in the chemical trend within the NYT around Campi Flegrei favours the presence of a single vent rather than development of a ring fracture and multiple vents that were suggested by Orsi et al. (1991).

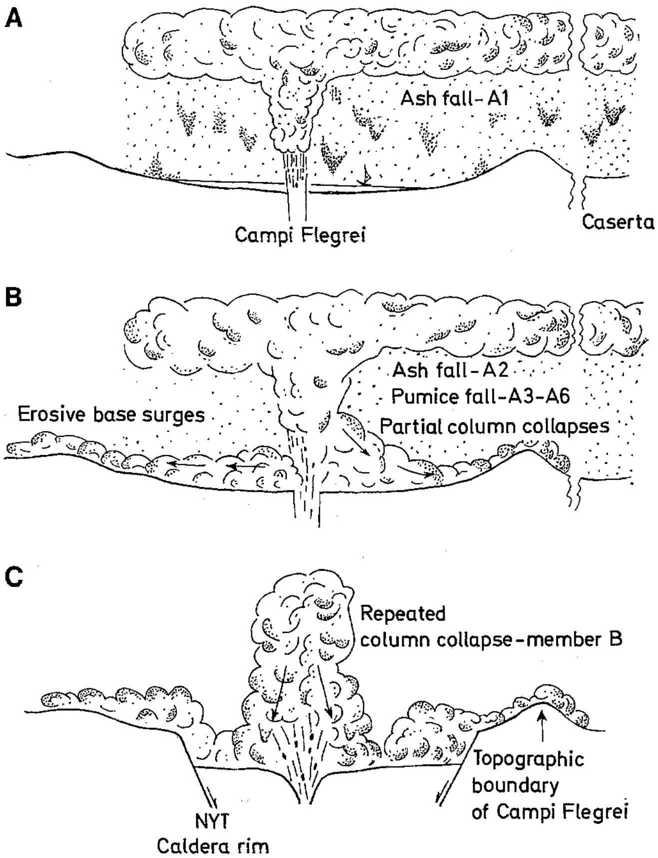

Fig. 11 A–C. Summary of the eruptive phases of the NYT eruption. **A** Development of a phreatoplinian eruptive column; ash fall from this initial phase forms unit A1. **B** Pyroclastic surges are formed either by partial collapses of the eruption column or directly from the vent. Occasional magmatic pulses produce pumice fall. The deposits produced by this phase form the remainder of member A. **C** Repeated column collapse produces numerous pyroclastic flows that give rise to the deposits of member B. The presence of a coarse proximal facies at the base of member B may indicate the onset of caldera collapse at the start of this phase

Conclusions

On the basis of field relations and laboratory analysis different outcrops of yellow tuff have been correlated in Campi Flegrei and attributed to the single formation of the Neapolitan Yellow Tuff (NYT), for which two distinct members (A and B) can be recognised.

The basal unit A1 of member A has been identified both in Campi Flegrei, Naples and in the Campanian Plain and represents the marker horizon of the formation. The regular decrease in thickness of the unit A1 with distance from the source and its constant thickness over strong topography suggests a fall origin of phreatoplinian dimensions. Its distribution indicates that the source of the NYT was probably in the northeastern sector of Campi Flegrei. The same source region is implied by the location of the coarse proximal facies of member B.

The NYT is the result of a complex alternation between phreatomagmatic and magmatic activity, involving eruption from a zoned trachytic magma body derived by crystal fractionation of a single trachytic parent magma. The first part of the eruption, producing member A, was dominated by discrete explosions with a variable magma/water ratio that produced fallout of both ash and lapilli, as well as pyroclastic surges. The second phase, associated with member B, involved deposition of a complex sequence of pyroclastic flows. Partial evacuation of the magma chamber resulted in formation of a caldera, ~10km in diameter, which is presently partly buried under more recent products. The total volume of erupted products has been estimated at ~50km^3 DRE.

Acknowledgements. Part of this work was carried out within the scope of a PhD thesis (CS). Dick Fisher and Luigi La Volpe are thanked for field discussions, and Grant Heiken for field discussions and useful comments concerning the SEM. L La Volpe and P Dellino are acknowledged for use of the Coulter counter at the Università di Bari. V Morra is also thanked for assistance with the XRF analyses. Chris Kilburn and Angus Duncan are thanked for their comments on an earlier version of this paper. We would like to thank Roberto Scandone for hospitality, many discussions and improving the manuscript. The Royal Society of Great Britain is acknowledged for funding to PC. The constructive comments of Jocelyn McPhie and two anonymous reviewers are appreciated.

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Editorial responsibility: T. H. Druitt