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Volcanological and geochemical features of the products of the Fiumicello eruption, Procida island, Campi Flegrei (southern Italy)

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Abstract. — A volcanological and geochemical characterization of the products of the Fiumicello eruption is here proposed. The volcanological features of the deposits, representing both a "proximal" and a "distal" facies, suggest that the eruption dynamics were quite similar to those of many other Campi Flegrei events, being characterized by both purely magmatic and phreatomagmatic phases. The physical parameters of the eruption, like its relatively low magnitude, the height of the eruption column and the dispersion of the products, are still comparable to those of many other events which characterized Campi Flegrei's volcanological evolution.

The mafic composition of the products of the Fiumicello eruption is rather unusual within the context of the Campi Flegrei district, largely dominated by highly evolved products. Therefore, the study of the products of this eruption gives an almost unique opportunity to investigate Campi Flegrei's plumbing system. Anyway, major- and trace element geochemistry, as well as mass-balance results, show that Fiumicello products can not be considered as representative of primary melts compositions.

The geochemical vertical variations observed within the products of the eruption suggest that the Fiumicello event was fed by a density stratified magma chamber. The existence of such reservoir structures has already been proposed for other Campi Flegrei eruption and, therefore, their development seems to be a very important process in the framework of the evolution of the Campi Flegrei magmatic system.

Riassunto. — È stato effettuato uno studio vulcanologico e geochimico dei prodotti dell'eruzione di Fiumicello. Le caratteristiche vulcanologiche dei prodotti studiati, presenti sia in facies "prossimale" che in facies "distale", suggeriscono che le dinamiche eruttive siano state molto simili a quelle di molti altri eventi della storia vulcanologica dei Campi Flegrei, caratterizzati da fasi sia magmatiche che freatomagmatiche. I parametri fisici dell'eruzione, come la sua portata relativamente ridotta, l'altezza della colonna eruttiva e la dispersione dei prodotti, sono anch'essi paragonabili a quelli che hanno caratterizzato molti altri eventi che hanno segnato l'evoluzione vulcanologica del distretto.

Il chimismo basico dei prodotti dell'eruzione di Fiumicello rappresenta una caratteristica piuttosto inusuale nel contesto dei Campi Flegrei, dominati da prodotti dall'elevato grado di evoluzione. Lo studio di tali prodotti, pertanto, offre la rara occasione di analizzare le caratteristiche delle vulcaniti meno evolute del distretto. Ad ogni modo, la geochimica degli elementi maggiori ed in tracce ed i risultati delle modellizzazioni dei processi di evoluzione magmatica, indicano che i prodotti di Fiumicello non possono essere considerati rappresentativi dei magmi primitivi dei Campi Flegrei.

Le variazioni geochimiche verticali osservate nei prodotti di Fiumicello sembrano suggerire che l'eruzione sia stata alimentata da una camera magmatica

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stratificata per densità. L'esistenza di simili strutture è stata già in precedenza proposta da altri autori per altre eruzioni dei Campi Flegrei, e pertanto sembrerebbe che lo sviluppo di tali camere magmatiche costituisca un processo molto ricorrente ed importante nell'ambito dell'evoluzione del sistema magmatico flegreo.

KEY WORDS: *Campi Flegrei, Volcanology, Fiumicello, Procida Island.*

INTRODUCTION

The Fiumicello volcano is one of the five volcanic complexes constituting the backbone of Procida Island, which belongs to the Campi Flegrei volcanic field, southern Italy (Fig. 1). The products of Procida are rather unusual if considered within the general geochemical framework of the Campi Flegrei district. In fact, they are mainly represented by relatively "primitive" compositions (i.e., shoshonitic basalts and shoshonites; D'Antonio and Di Girolamo, 1994), especially if considered in the light of the absolute predominance of highly evolved lithotypes (i.e., trachytes) among the products of the Campi Flegrei district.

The Fiumicello volcano is a tuff-ring edifice whose volcanic activity strongly resembles those of many other phlegrean volcanoes, in terms of intensity, eruptive style and volume of erupted products. The choice of focusing our attention on the products of the Fiumicello volcano is therefore largely legitimated, both on geochemical and volcanological grounds. In fact, while it could be taken as a good exemplification of a typical phlegrean monogenetic edifice, it is also characterized by low-differentiation products, which therefore represent a very rare opportunity to investigate on Campi Flegrei most primitive products' characteristics.

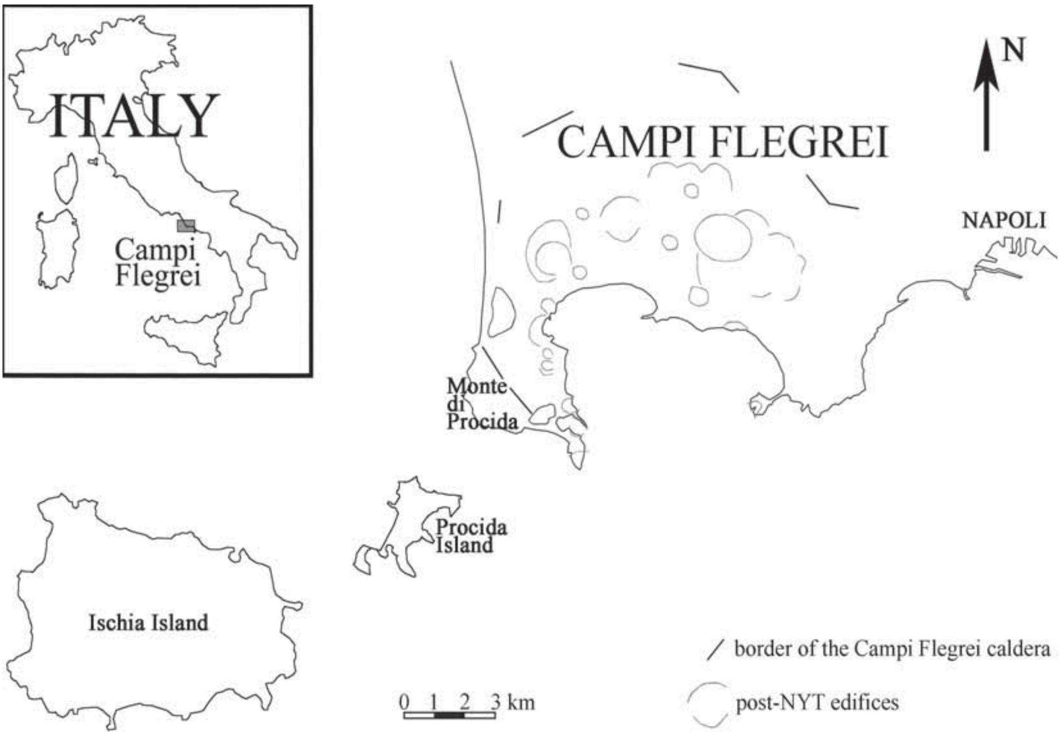


Fig. 1 – Location of the Campi Flegrei volcanic district.

The Campi Flegrei district

The Campi Flegrei is a volcanic field located immediately west of the city of Napoli, southern Italy (Fig. 1). Its volcanic history is characterized by a great number of eruptions, giving birth to mainly monogenetic edifices, emplacing huge volumes of pyroclastic rocks and very sporadic small-scale lava flows. Generally speaking, phlegrean volcanism includes not only the activity developed on the continent (the Campi Flegrei *strictu sensu*) but also the activity developed on the Islands of Ischia and Procida, which share many geological, volcanological and petrological similarities with Campi Flegrei (Di Girolamo et al., 1984, 1995).

The beginning of phlegrean volcanism is not yet well constrained. It has been suggested that "insular" phlegrean activity largely predates "continental" one. The oldest products seem to be those constituting the base of the sequence on Ischia, were the oldest occurring deposits, even if never directly dated, seem to date back to at least 150 ka, on the basis of stratigraphic and geochronological considerations made by several authors (e.g., Poli et al., 1987; Vezzoli, 1988). Activity on Procida probably developed only later, with the oldest products probably being deposited around 70 ka, as proposed by De Astis et al. (2004). "Continental" phlegrean volcanism was probably even younger, as the oldest known deposits showed an $^{40}Ar/^{39}Ar$ age of ~58 ka (Pappalardo et al., 1999). It is interesting to note, however, that this age limit should be probably brought further back because of the occurrence, in a lower stratigraphic position with respect the aforementioned 58 ka old deposits, of some pyroclastic deposits which seem to be attributable to Campi Flegrei volcanism (Ricci, 2000).

The main events which characterized the volcanological evolution of the Campi Flegrei were those responsible of the emplacement of the Campanian Ignimbrite (CI, ~37-39 ka, $^{40}Ar/^{39}Ar$; Deino et al., 1992, 1994; Ricci, 2000; Ricci et al., 2000; De Vivo et al., 2001) and the Neapolitan Yellow Tuff (NYT, ~15 ka, $^{40}Ar/^{39}Ar$; Deino et al., 2004; Insinga et al., 2004) deposits. The products of the two eruptions have largely been used as marker horizons, given their very common and diffuse occurrence. Moreover, the two events have been considered as very important landmarks in the framework of the volcanological evolution of the area, especially in the light of the very deep morphological and structural modifications caused by the occurrence of these two highly energetic eruptions. As a consequence, several authors have used them to make schematizations of phlegrean activity, which could be therefore broadly subdivided into pre-CI (the oldest phase of activity), post-CI (successive to the CI event and to the formation of the Campi Flegrei caldera, probably at least partially related to the CI eruption; e.g., Rosi and Sbrana, 1987; Orsi et al., 1992; 1996; Perrotta et al., 2006) and post-NYT (the most recent period of activity).

At the present, volcanism at Campi Flegrei is limited to fumarolic and hydrothermal manifestations and sporadic bradiseismic events. The last volcanic eruption was the historical Monte Nuovo 1538 A.D. eruption (Di Vito et al., 1987; Lirer et al., 1987b; D'Oriano et al., 2005; Piochi et al., 2005).

The Campi Flegrei products are almost exclusively pyroclastic, with very rare effusive events. The products show a clear potassic affinity, belonging to the potassic series of the Roman Comagmatic Province (Di Girolamo et al., 1984), corresponding to the KS of Conticelli et al. (2002) and Conticelli et al. (2004). Rock compositions range from shoshonitic basalts to trachytes and phonolites, with the most differentiated products, and particularly the trachytes, being by far the dominant lithotypes. It is interesting to note that the most primitive lithotypes are particularly recurrent on Procida Island. This makes the study of Procida products of great importance because it provides the opportunity, very rare in the Campi Flegrei region, to investigate on phlegrean nearly-primary magmas' characteristics.

Rock textures vary from totally aphyric to slightly porphyritic (up to ~30% of phenocrysts), with the Porphyricity Index (P.I.) being inversely linked to the degree of differentiation. The most abundant mineral phases are represented by clinopyroxene, plagioclase, sanidine, biotite and magnetite. Olivine is confined to the least evolved lithotypes, from shoshonitic basalts to latites. Phlegraean volcanic rocks are characterized by very low TiO_2, Nb, and Ta values, high K_2O and Al_2O_3 concentrations and high LILE/HFSE and LREE/HREE ratios.

THE ISLAND OF PROCIDA

The island of Procida (Fig. 2a) represents a still poorly studied part of the Campi Flegrei volcanic field. It is located in the south-western part of the district, constituting a very evident NE-SW alignment with the "continental" Campi Flegrei and the island of Ischia. Despite the wealth of volcanological and geochemical studies carried out in the last 30 years over the Campi Flegrei products, there are still very few works regarding Procida products, and, with very few exceptions

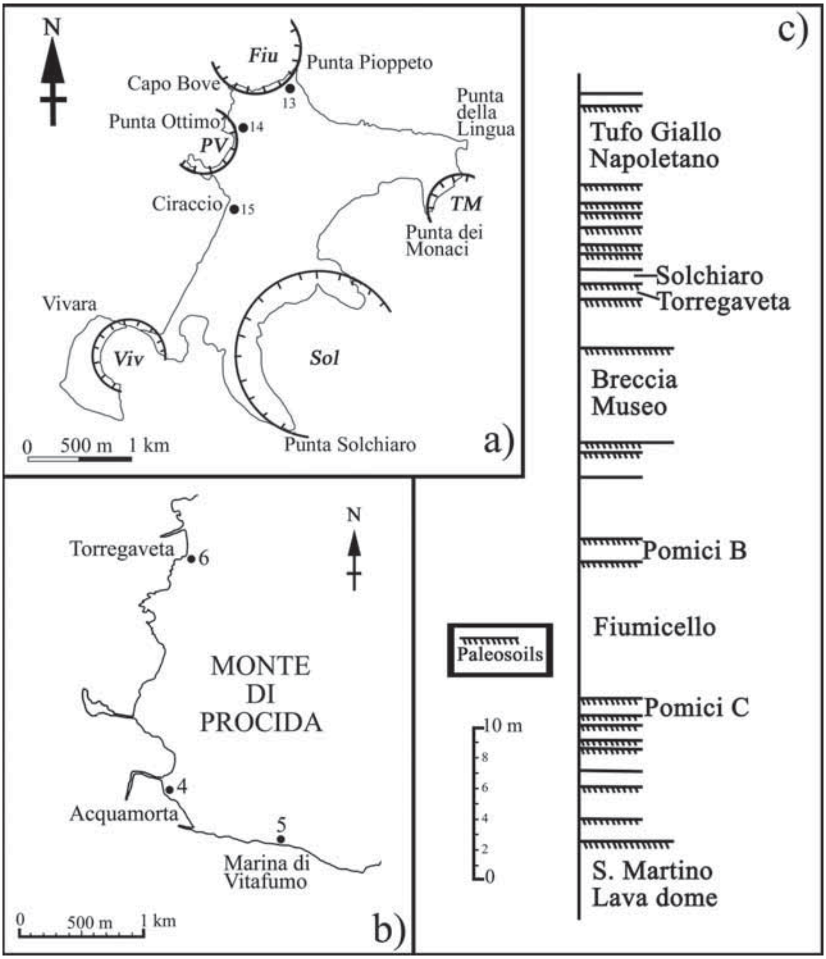


Fig. 2 – a) Map of the island of Procida. Black dots indicate the localization of the studied stratigraphic sections: 1) Punta Pioppeto; 2) Punta Ottimo; 3) Ciraccio. Labels in bold italics indicate the presumed location of the five eruptive craters of the island (***PV*** = Pozzo Vecchio; ***Viv*** = Vivara; ***TM*** = Terra Murata; ***Fiu*** = Fiumicello; ***Sol*** = Solchiaro). b) Map of the Monte di Procida area, south-western sector of the Campi Flegrei. Black dots indicate the localization of the studied stratigraphic sections: 4) Acquamorta; 5) Marina di Vitafumo; 6) Torregaveta. c) Schematic stratigraphic section of the deposits occurring at the Acquamorta locality. The products of some of the major Campi Flegrei eruptions outcropping in the area have been reported to give a rough idea of the chronostratigraphic collocation of the Fiumicello event (see text for further indications).

(i.e., D'Antonio and Di Girolamo, 1994; De Astis et al., 2004), most of them are at least older than 15 years (e.g., Cristofolini et al., 1973; Di Girolamo and Stanzione, 1973; Albini et al., 1977; Pescatore and Rolandi, 1981; Di Girolamo et al., 1984; Rosi et al., 1988).

Procida stratigraphic sequence is mainly made up by the products of the five monogenetic volcanoes which constitute the backbone of the island: Vivara, Pozzo Vecchio, Terra Murata, Fiumicello and Solchiaro (Fig. 2a). These edifices seem to have been active over the last 70 ka (De Astis et al., 2004), but none of the outcropping deposits has been directly dated. Their products are almost exclusively pyroclastic deposits, with the exception of the Punta Ottimo lava dome, representing the only effusive episode of Procida activity (Di Girolamo and Stanzione, 1973; Di Girolamo et al., 1984). These volcanic units are interbedded with minor volcanic products coming from "continental" Campi Flerei, Ischia and small submarine volcanic centers (Rosi et al., 1988; De Astis et al., 2004).

A comprehensive stratigraphic schematization of volcanic products occurring on Procida Island has been proposed by De Astis et al. (2004), starting with the products of the three edifices of Vivara, Terra Murata and Pozzo Vecchio. These authors have collocated the three units in equivalent stratigraphic position, given the lack of both stratigraphic contacts between them and of absolute age determinations of their products. Above these deposits lies a sequence comprising products erupted from the Formiche di Vivara submerged vent, unidentified Procida volcanics and products of Ischia island activity (the *pomici pliniane C* of the Pignatiello formation; Rosi et al., 1988; De Astis et al., 2004). The stratigraphic sequence is then characterized by the occurrence of the Fiumicello volcano deposits, followed by another sequence of Ischia volcanics (i.e., the *pomici pliniane B* of the Pignatiello formation and the Monte S. Angelo and the *Tufo Verde del Monte Epomeo* formations; Rosi et al., 1988; De Astis et al., 2004). Deposits coming from the Formiche di Vivara submerged vent and from the continental part of the Campi Flegrei (i.e., the Campanian Ignimbrite and the Torregaveta formations) precede the occurrence of the Solchiaro volcano products, the youngest among Procida volcanics [<19-17 ka, based on ^{14}C datings on underlying paleosoils reported by Alessio et al. (1976) and Lirer et al. (1991)]. The highest products occurring are those forming the so-called *Tefra superiori* unit (<14 ka, ^{14}C; Rosi et al., 1988), made up of several pyroclastic units, probably related to "continental" Campi Flegrei and recent Ischia activities, with numerous interbedded paleosoils.

The Fiumicello volcano

The volcanic center of Fiumicello was probably located in the north-western part of the island, between Punta Pioppeto and Capo Bove (Fig. 2a), where its south-eastern half is still preserved, previously recognized by several authors (Di Girolamo and Stanzione, 1973; Di Girolamo and Rolandi, 1979; Pescatore and Rolandi, 1981; Rosi et al., 1988; De Astis et al., 2004). The morphology of the remnants of the edifice seems to indicate that the Fiumicello volcano was a tuff-cone edifice (Cas and Wright, 1987); however, according to De Astis et al. (2004) it should be considered as a tuff-ring edifice.

The proximal facies are represented by a lithified, massive, grey to yellow tuff deposit, up to 30 m in thickness. Iuvenile clasts are represented by scoria bombs and scoriaceous lapilli. Lithic clasts are present as well, mainly represented by coarse lava blocks up to 50 cm in diameter, commonly forming impact sags. Sand wave structures are also very common features of proximal facies. As the distance from the possible vent source increases, the deposit gradually becomes more and more evidently stratified, with the distal facies showing a very evident plane-parallel alternation of layers mainly made up of dark grey scoriaceous lapilli and light grey ashy layers. The transition between these two facies is clearly visible along the coastline between Punta Pioppeto and Punta Ottimo, were the Fiumicello deposits can be followed continuously.

Both the proximal and distal facies are very easily identifiable because of their occurrence between two plinian pumice fallout layers, which Rosi et al. (1988) ascribed to the Pignatiello formation of Ischia (respectively, the *pomici pliniane C* at the bottom and the *pomici pliniane B* at the top of the Fiumicello formation). The association of the three deposits represents a very useful marker horizon within the whole south-western sector of the Campi Flegrei.

The exact age of the volcano-building event is still unknown. Alessio et al. (1976) gave an age of ~32 ka for the Fiumicello deposits, on the basis of ^{14}C datings performed on underlying paleosoils. This value appears to be unreliable, given the ^{14}C age values obtained for the products of the Pignatiello formation, which yielded an age range of 74-55 ka (Vezzoli, 1988). Moreover, Fiumicello deposits always occur, both on Procida island and on the Monte di Procida cliffs, in lower stratigraphic position with respect to breccia deposits which gave an $^{40}Ar/^{39}Ar$ age of ~39 ka (Ricci, 2000; Ricci et al., 2000; Perrotta et al., 2004). Therefore, it seems that the Fiumicello eruption should be considered to have occurred before 55 ka.

DESCRIPTION OF THE ANALYZED STRATIGRAPHIC SECTIONS

The Fiumicello formation has been observed and sampled in six different locations, three on the Procida island (Punta Pioppeto, Punta Ottimo and Ciraccio localities; Fig. 2a), and three on the Monte di Procida cliffs (Acquamorta, Torregaveta and Marina di Vitafumo localities; Fig. 2b), representing, respectively, the proximal and the distal facies. It is important to stress that the outcrops of the products of the distal facies are limited only to those just mentioned. This is only partly due to the very limited areal distribution of the products. It is here suggested that the sinking of the area immediately north of the Monte di Procida area (Fig. 1), which collapsed after the eruption of the CI (Rosi et al., 1983; Rosi and Sbrana, 1987; Perrotta et al., 2006), must have had a role in this direction. As a consequence, deposits older than the CI were brought to deeper levels and, eventually, were covered by the products of more recent activity.

In order to better understand the exact chronostratigraphic collocation of the Fiumicello deposits within the eruptive history of the Campi Flegrei district, a schematic stratigraphic section of the deposits occurring along the coastal cliffs of the Acquamorta locality is shown in Fig.2c. In this locality the Fiumicello deposits are part of a thick sequence of Campi Flegrei deposits spanning the entire spectrum of activity of the district: the older, pre-CI deposits (e.g., the S. Martino lava dome; Di Girolamo et al., 1984; Perrotta et al., 2004), the products of the CI eruption (i.e., the Breccia Museo formation; Perrotta and Scarpati, 1994; Melluso et al., 1995; Perrotta et al., 2004), some pre-NYT deposits (e.g., Torregaveta; Perrotta et al., 2004), the deposits of the NYT eruption, and the products of the recent post-NYT activity.

In this section a description of each of the above-mentioned stratigraphic sections will be reported.

PROCIDA OUTCROPS

Punta Pioppeto section

The occurring deposit (Fig. 3) is made up of a typical proximal facies, indicating that the original vent was probably very close to this location. The total exposed thickness of the outcrop is of about 30 m, but both the bottom and the top of the deposit are not visible. The iuvenile and lithic elements are very coarse, reaching diameters up to 50 cm. Iuvenile elements are represented by scoria clasts, while lithic clasts are mainly dark lavas. The cineritic matrix is generally zeolitized, showing the typical yellow colour of this kind of post-depositional alteration, already observed by Di Girolamo and Stanzione (1973). The structure is massive, with bomb sags and sand wave structures also occurring. Given the very deep alteration of the occurring scoria clasts, samples collected at this locality are represented only by lithic clasts, labelled FF1 to FF6.

Punta Ottimo section

The outcropping sequence represents a sort of link between typical proximal and typical distal facies. It is characterized by a very crude alternation of scoriaceous lapilli layers and cineritic layers (Fig. 3), which becomes more and more evident as the distance from the possible vent (i.e., the Punta Pioppeto area) increases. Some individual levels still show structural features typical of proximal facies, such as bomb sags, sand wave stratification and coarse ballistic lithic clasts (made up of both lava and tufaceous clasts). The base of the deposit lies above a pumiceous fallout level, which characterizes the top of the sequence as well (the aforementioned *pomici pliniane C* and *B* of the Pignatiello Formation). The total measured thickness is of about 8.70 m. Samples of scoriaceous lapilli, named FCN1 to FCN3 (from bottom to top) were collected.

Ciraccio section

The Fiumicello deposit occurring at this locality is represented by a thin massive cineritic body (~1.50 m), with dispersed fine-grained scoriaceous lapilli (mean diameter ~3 cm). As usual, the deposit is bracketed by two evident pumice fallout layers. Only one sample, labelled FCC, was collected in this locality (Fig. 3).

Monte di Procida outcrops

Acquamorta section

The section occurring at the Acquamorta locality is probably the most characteristic of the distal

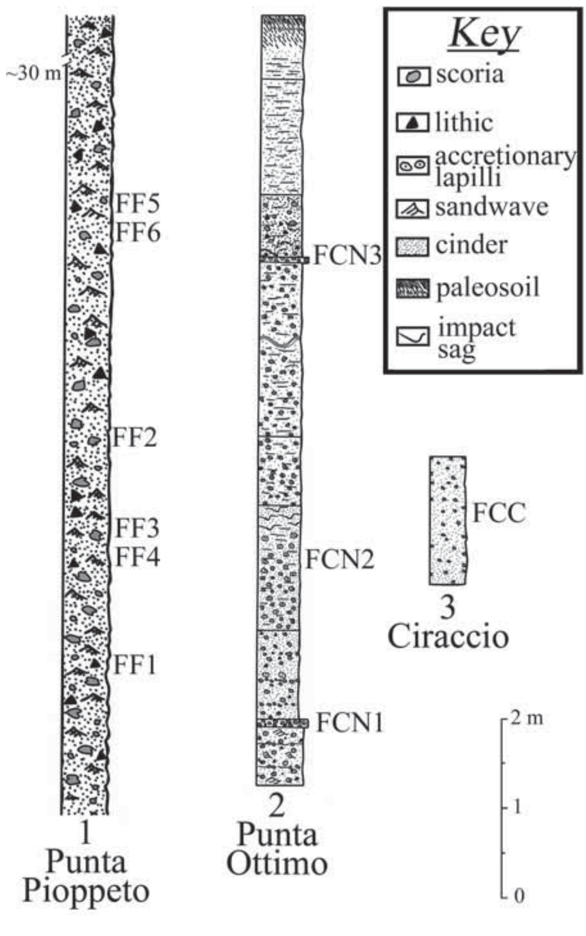


Fig. 3 – Stratigraphic sections of the "proximal" outcrops of the Fiumicello deposits occurring in the studied localities of the Procida Island. Labels indicate collected samples and their stratigraphic position.

facies of the Fiumicello deposit and, therefore, it has been subject to a detailed sampling (samples of scoriaceous lapilli named from FAM1 to FAM19, from bottom to top; Fig. 4). The sequence lies on the pumiceous fallout layer of the *pomici pliniane C* deposit and is represented by a regular alternation of layers of scoriaceous lapilli (with minor lithic lava clasts) and cineritic layers, with a total thickness of 8.74 m.

Lapilli layers usually show a good sorting, but locally it is possible to recognize a slight grading (both direct and inverse) within a single layer. The size of lapilli clasts (~2-2.5 cm) is substantially the same all along the vertical extension of the deposit. Anyway, it is possible to recognize a very slight tendency to smaller diameters moving upsection (i.e., generally $\geq$1 cm). Lithic clasts, commonly represented by dark lavas, are also present, generally showing slightly smaller medium diameters with respect to scoria clasts.

Locally, the cineritic layers also include some accretionary lapilli, suggesting a possible phreatomagmatic character of some phases of the eruption. The occurrence of cineritic layers is generally minor with respect to lapilli layers in the lowest portions of the deposit, whereas in the upper portions they are generally more commonly observed. The thickness of individual layers does not seem to follow a specific trend, with very narrow alternation of scoriaceous and cineritic layers being observed both in the lowest and in the highest parts of the section.

The top of the deposit is marked by a humified horizon about 30 cm thick, above which lies the *pomici pliniane B* pumiceous fallout deposit.

Marina di Vitafumo section

Similarly to the Acquamorta section, the Marina di Vitafumo section is a very typical distal facies of the Fiumicello deposit, showing a very regular alternation of scoriaceous lapilli and cineritic layers. As in the Acquamorta section, individual scoriaceous lapilli layers are generally well sorted and seem to be characterized by smaller clasts in the upper portions of the deposit, where their presence is subordinate with respect to cineritic layers (Fig. 4). The alternation of individual layers appears to be less narrow than in the Acquamorta section, but still with no specific recognizable trend (i.e., neither narrower nor broader moving upsection).

The sequence (total thickness: 5.22 m) is again bracketed by the pumice fallout deposits of the Pignatiello formation. Scoria samples FVF1 and FVF2 were collected.

Torregaveta section

A 4.06 m thick alternation of scoriaceous lapilli and cineritic layers, very similar to those observed in the other outcrops occurring on the Monte di Procida cliffs, characterizes this section, still opened and closed by the deposits of the Pignatiello formation.

The general features recognized within the deposit are very similar to those observed in the previously described distal facies (Fig. 4). With respect to the Acquamorta and Marina di Vitafumo sections the alternation of scoriaceous and cineritic layers seems more regular for the whole section, with no similar differences of thickness between the lowest portions (generally characterized by thicker levels in the previous sections) and the highest ones. Scoria samples named FTR1 to FTR6 (in stratigraphical order) were collected.

Eruptive and depositional dynamics

The eruptive style of the Fiumicello event seems to have been predominantly phreatomagmatic, given the high fragmentation and the common occurrence of accretionary lapilli observed in the deposits of the proximal exposures (i.e., the Punta Pioppeto and Punta Ottimo sections). These deposits are probably derived by low energy pyroclastic currents, given the very limited areal extent of the products, whose occurrence is restricted to the outcrops located in the very immediate proximities of the vent area.

The eruption seems to have also experienced sustained column phases, as indicated by the occurrence of cineritic levels in the distal exposures of the Monte di Procida area. The high fragmentation and the occurrence of accretionary lapilli in these deposits, in fact, strongly support their derivation from a similar phreatomagmatic phase. Their deposition is therefore attributable to sustained column conditions, during which the dispersion of the products was controlled by the direction of the local dominating winds (i.e., mainly from W-SW to E-NE, as for the great majority of Campi Flegrei fall deposits; e.g., Lirer et al., 1987a; Rosi and Sbrana, 1987; Scarpati et al., 1993; de Vita et al., 1999; Rosi et al., 1999; Lirer et al., 2001; Perrotta and Scarpati, 2003; Isaia et al., 2004; Orsi et al., 2004).

The effective occurrence of sustained column phases during the Fiumicello eruption is also suggested by the presence of the scoriaceous lapilli levels regularly intercalated with the cineritic levels in the distal exposures. The lithological characteristics of these levels (i.e., good sorting, angular clasts, absence of cineritic matrix), in fact, strongly support their provenance from a pyroclastic fall event. Moreover, the absence of matrix within this scoriaceous levels is also a good clue for their belonging to magmatic eruptive phases, during which, therefore, the fragmentation of the magma was driven only by magmatic gases while magma/water interaction was strongly

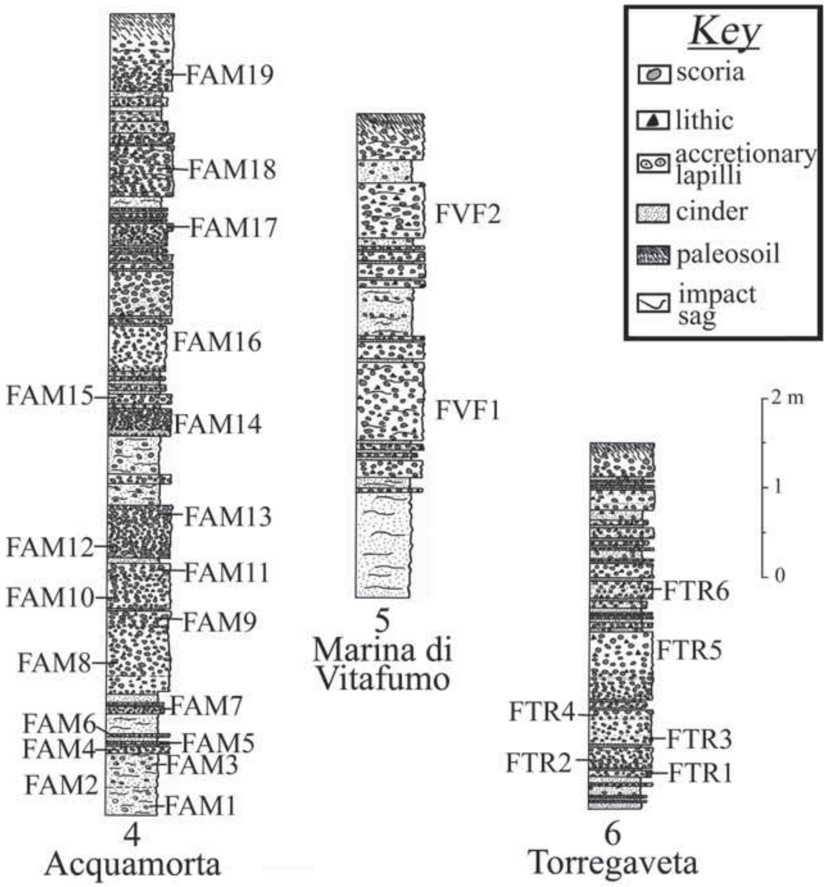


Fig. 4 – Stratigraphic sections of the "distal" outcrops of the Fiumicello deposits occurring in the studied localities of the Monte di Procida area. Labels indicate collected samples and their stratigraphic position.

reduced or even completely hindered. The granulometric differences between scoriaceous lapilli of the different levels should be interpreted as an evidence of the instability of the eruptive column.

PHYSICAL PARAMETERS OF THE FIUMICELLO ERUPTION

Volume of the fallout products

The volume of the fallout products has been estimated using the equations firstly proposed by Pyle (1989), then modified by Fierstein and Nathenson (1992). These models are based on the assumption that the thickness (T) of a fall deposit decreases moving away from the vent following the exponential law:

$$T = T_0 * e^{(-K*\sqrt{A})}$$

where T_0 is the maximum thickness of the fallout deposit (i.e., at the vent source), A is the area enclosed within the isopach relative to a specific value of T, and K is the slope of the straight line defined by plotting ln(T) versus $\sqrt{A}$. The equation for the calculation of the volume of the deposit (V) is then obtained by integration, and results as:

$$V = 2 * T_0 / K^2$$

This method has been applied only to the fallout products of the magmatic phases of the Fiumicello eruption. Therefore, both the deposits of the phreatomagmatic phases (i.e., those occurring in the proximal outcrops), and the cineritic levels found in the sections observed in the sections of the Monte di Procida area have been excluded from the performed calculations. Consequently, isopach maps have been drawn (Fig. 5), taking in consideration only the scoriaceous lapilli levels, whose thickness have been summed for each of the distal section, yielding a total thickness of 584 cm at Acquamorta, 289 cm at Vitafumo and 226 cm at Torregaveta. The volume of the deposit has been calculated taking into account only the area enclosed within the isopachs of 200 and 300 cm, and therefore represents only a minimum value. The obtained K value is 0.339, from which a T_0 (i.e., the maximum thickness of the deposit, obtained by assuming A = 0) value of 744 cm has been extrapolated. The resulting value of erupted volume relative to the magmatic fallout deposit is 0.13 km^3.

Height of the eruptive column of some sustained-column phases of the eruption

The height of the eruptive column, relatively to some phases of sustained column activity, has been calculated according to the model of Carey and Sparks (1986). The method is based on the identification of two parameters: the downwind range, representing the distance between the vent and the intersection of a specific isopleth with the dispersal axis, and the crosswind range, corresponding to the half-axis of the ellipsoidal curve enclosed within the considered isopleth. The values of the two parameters are plotted together in a binary diagram in which corresponding column heights and wind velocities are then derived.

Several isopleth maps, of both scoriaceous lapilli and lithic clasts, have been drawn for the fallout deposits of the Fiumicello eruption. Among all these maps, two well-correlated levels were chosen, one for scoriaceous lapilli and another one for the lithic clasts. The scoriaceous lapilli

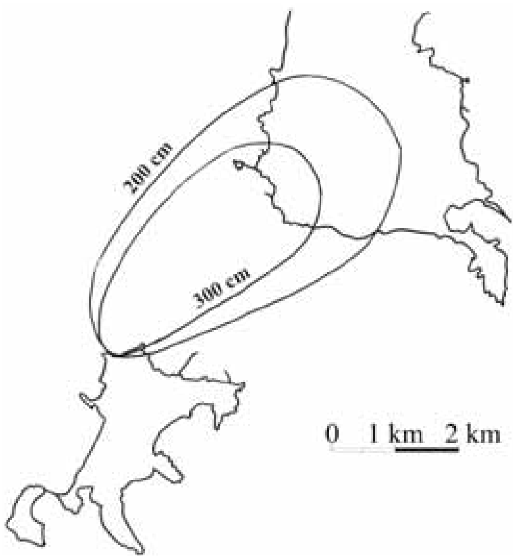


Fig. 5 – Isopach map relative to the fallout products of the Fiumicello eruption. See text for further informations.

measured in the selected level have maximum diameters of 1.2, 1.8 and 2.4 cm, and consequently isopleths for 1 cm and 2 cm were built (Fig. 6a). The values of the downwind and crosswind ranges obtained are, respectively, 5.6 km and 1.63 km for the 1 cm isopleth, 4.65 km and 1.05 km for the 2 cm isopleth. A hydraulic equivalent scale ranging from 0.8 cm – 2500 kg/m^3 to 8 cm – 250 kg/m^3 was chosen and applied to the 1 cm isopleth data, given the correspondence, within this scale, of 1.3 cm elements to a density of 1500 kg/m^3, in good agreement with density values commonly reported for Campi Flegrei scoriae (e.g., D'Oriano et al., 2005). From these data, a column height ranging from 6.8 and 13.8 km, and a wind velocity of about 20 m/s (Fig. 7a) were obtained.

Similar calculations have been performed for lithic clasts, whose measured maximum diameters in the chosen well-correlated level were 1.8, 3.1 and 4 cm. Isopleths for 2 cm and 3 cm were then built (Fig. 6b). The resulting values for downwind and crosswind ranges are, respectively, 5.55 km and 1.5 km for the 2 cm isopleth, 4.88 km and 1.05 km for the 3 cm isopleth. The chosen hydraulic equivalent scale ranges from 3.2 cm – 2500 kg/m^3 to 16 cm – 500 kg/m^3, applied to the 3 cm isopleth data. Resulting column height values range from 6.8 and 13.8 km, with wind velocities of about 30 m/s (Fig. 7b). Both values are in good agreement with those obtained for the selected scoriaceous lapilli level. The quite high values for the calculated wind velocities seem to be in good accordance with the strongly asymmetrical dispersion of the products.

Petrography, mineralogy and geochemistry of the Fiumicello products

Petrographic features

The studied samples are mainly represented by scoriaceous lapilli. In addiction to these, six lithic samples were also collected from the Punta Pioppeto outcrop, in order to investigate also on the characteristics of the volcanic substratum below the Fiumicello volcano.

Scoria samples are moderately vesicular, generally ranging from aphyric to very slightly porphyritic, with a P.I. generally lower than ~10%. The main phenocryst phases are subhedral to euhedral clinopyroxene and plagioclase, sometimes forming little monomineralic aggregates. Anhedral olivine crystals, completely or almost completely altered to hiddingsite, are also present, but their abundance is very low (i.e., ~1-2%). Opaque oxides are common accessory

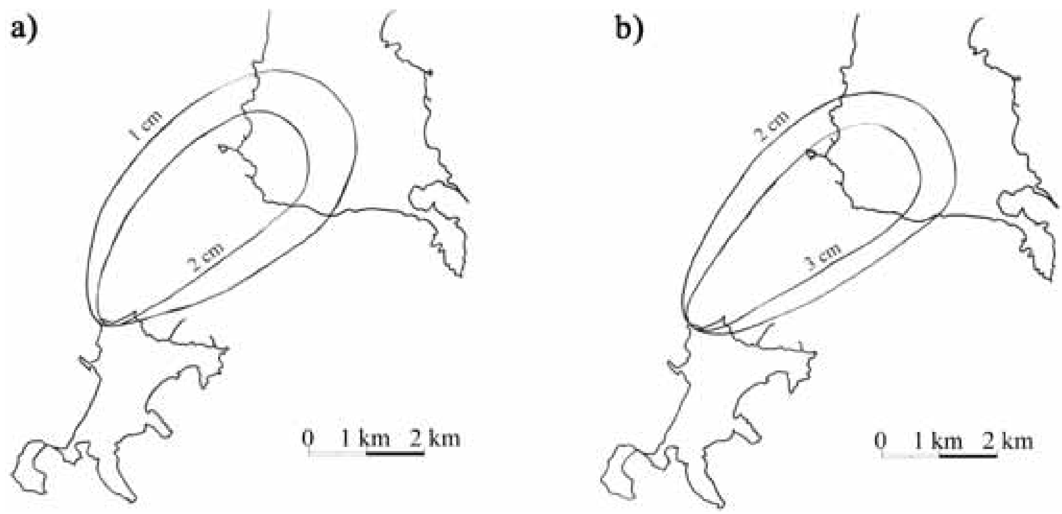
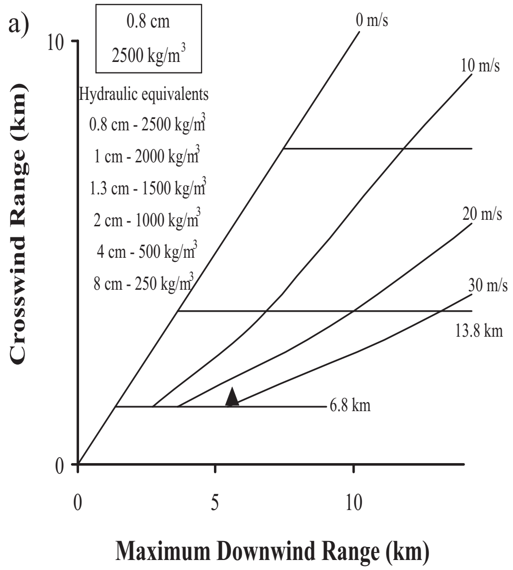


Fig. 6 – Isopleth maps relative to scoria (a) and lithic (b) clasts of two well-correlated layers of the products of the Fiumicello eruption. See text for further informations.



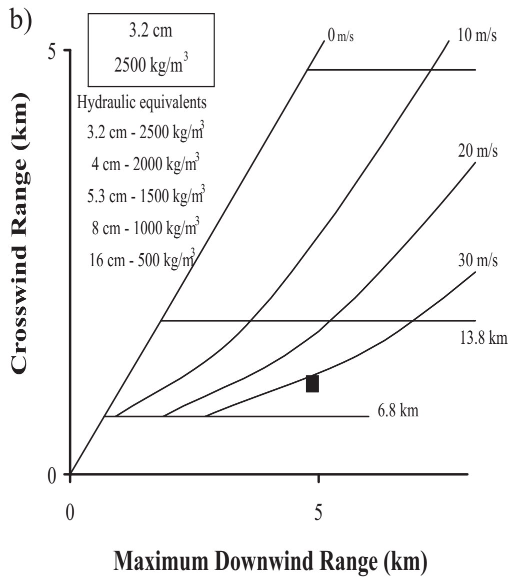


Fig. 7 – Calculation of the height of the eruption column relative to some phases of sustained column activity of the Fiumicello eruption, according to the method of Carey and Sparks (1986). Figures (a) and (b) refer, respectively, to scoria and lithic clasts of two well-correlated layers. See text for further informations.

phases, sporadically occurring as little subhedral to anhedral microphenocrysts. The groundmass is commonly made up of dark brown glass in which sometimes it is possible to recognize very little acicular plagioclase crystals, opaque oxides and sporadic clinopyroxenes.

Five lithic samples (FF1, FF2, FF3, FF5 and FF6) are represented by porphyritic lava clasts, with a paragenesis made up of clinopyroxene, plagioclase and olivine crystals, in order of abundance. Groundmass is only partially glassy, including the same phases present as phenocrysts plus anhedral opaque oxides. Lithic clast FF4 is still a porphyritic lava sample, but its paragenesis, differently from that of the previously described lithic samples, is dominated by very abundant large K-feldspar phenocrysts. Clinopyroxene and plagioclase are also present, generally occurring as less abundant smaller phases. The groundmass is almost completely made up of very little acicular feldspars with sporadic opaque oxides.

Petrochemical features

The samples of the Fiumicello eruption have been analyzed for major and trace elements by XRF; the data were then corrected according to the reduction methods of Franzini et al. (1972) and Leoni and Saitta (1976). Na_2O and MgO were determined by AAS; LOI values were obtained by standard gravimetric techniques.

Analyzed samples are mainly represented by shoshonitic basalts and latites, according to the classification diagram proposed for orogenic alkaline potassic rocks by Peccerillo and Taylor (1976), successively modified by Di Girolamo (1984) (Fig. 8). One trachytic lithic sample is also present.

Some of the samples, mostly represented by scoria clasts collected in the "distal" Monte di Procida outcrops, have shown compositions, probably due to the occurrence of alteration processes, which resulted into an alkali depletion and, as consequence, an indirect silica enrichment. As a confirmation to this hypothesis, the abnormally high LOI contents of these samples (i.e., 6.7-8.5%), usually coupled with unusual normative contents of qz (2.8-5.5%) and hy (6.2-10.9%; see table 1) should be noted. Similar post-depositional

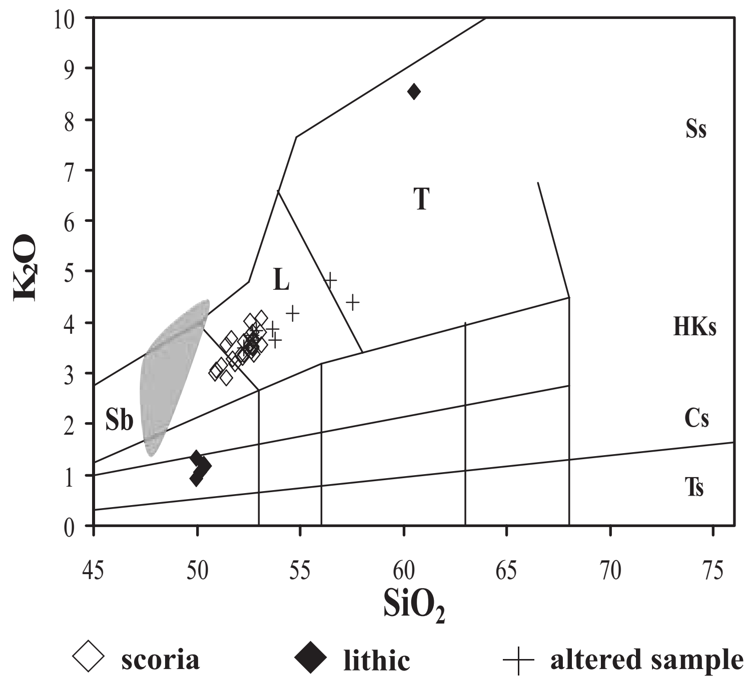


Fig. 8 – K_2O vs. SiO_2 classification diagram (Peccerillo and Taylor, 1976; Di Girolamo, 1984) for the Fiumicello samples. Empty and full diamonds are used for juvenile scoria samples and lithic samples, respectively. Crosses indicate altered samples (see text). Shaded grey area represents the compositional field of Fiumicello iuvenile samples taken from the literature (Di Girolamo and Rolandi, 1979; Di Girolamo et al., 1984; Pappalardo et al., 1999; De Astis et al., 2004). Sb = shoshonitic basalt; L = latite; T = trachyte; Ts = Tholeiitic series; Cs = Calcalkaline series; HKs = High K calcalkaline series; Ss = Shoshonitic series.

alteration processes have already been reported for Campi Flegrei products by Armienti et al. (1983).

Major- and trace elements binary variation diagrams typically show two groups of samples: a small "primitive" group consisting of lithic samples from Punta Pioppeto (with the only exception of lithic sample FF4), and a main group representing the compositions of all the collected iuvenile clasts (Fig. 9). The only trachyphonolitic lithic clast plots away from the two groups. The lithic group is characterized by very narrow ranges of compositions (e.g., SiO_2 49.9-50.4%, CaO 10.8-11.3%, K_2O 0.91-1.34%, Zr 83-94 ppm, Ni 19-28 ppm, Rb 30-58 ppm) and is represented by the least evolved samples of the entire set. The iuvenile group typically shows a larger compositional variability (e.g., SiO_2 50.9-57.5%, CaO 11.7-8.05%, K_2O 3.07-4.84%, Zr 128-227 ppm, Ni 20-38 ppm, Rb 123-166 ppm), with more evolved compositions with respect to the lithics of the previous group. Moreover, the lithic group is characterized by higher Na_2O and much lower K_2O/Na_2O (i.e., respectively, 4.27-4.92% against 2.40-4.30% and 0.21-0.28 against 0.75-1.49) with respect to the iuvenile group (see table 1). The trachyphonolitic lithic sample FF4 is the only lithic sample which does not show anomalously low K_2O/Na_2O values (i.e., ~1.62). It is characterized by the highest SiO_2 (60.5%), K_2O (8.55%) and Zr (339 ppm) values, and by the lowest TiO_2 (0.39%), Fe_2O_3 (3.33%), MgO (0.28%) and CaO (2.02%), given its highly evolved geochemical composition.

As a whole, the compositional data seem to suggest the existence of a genetic link between

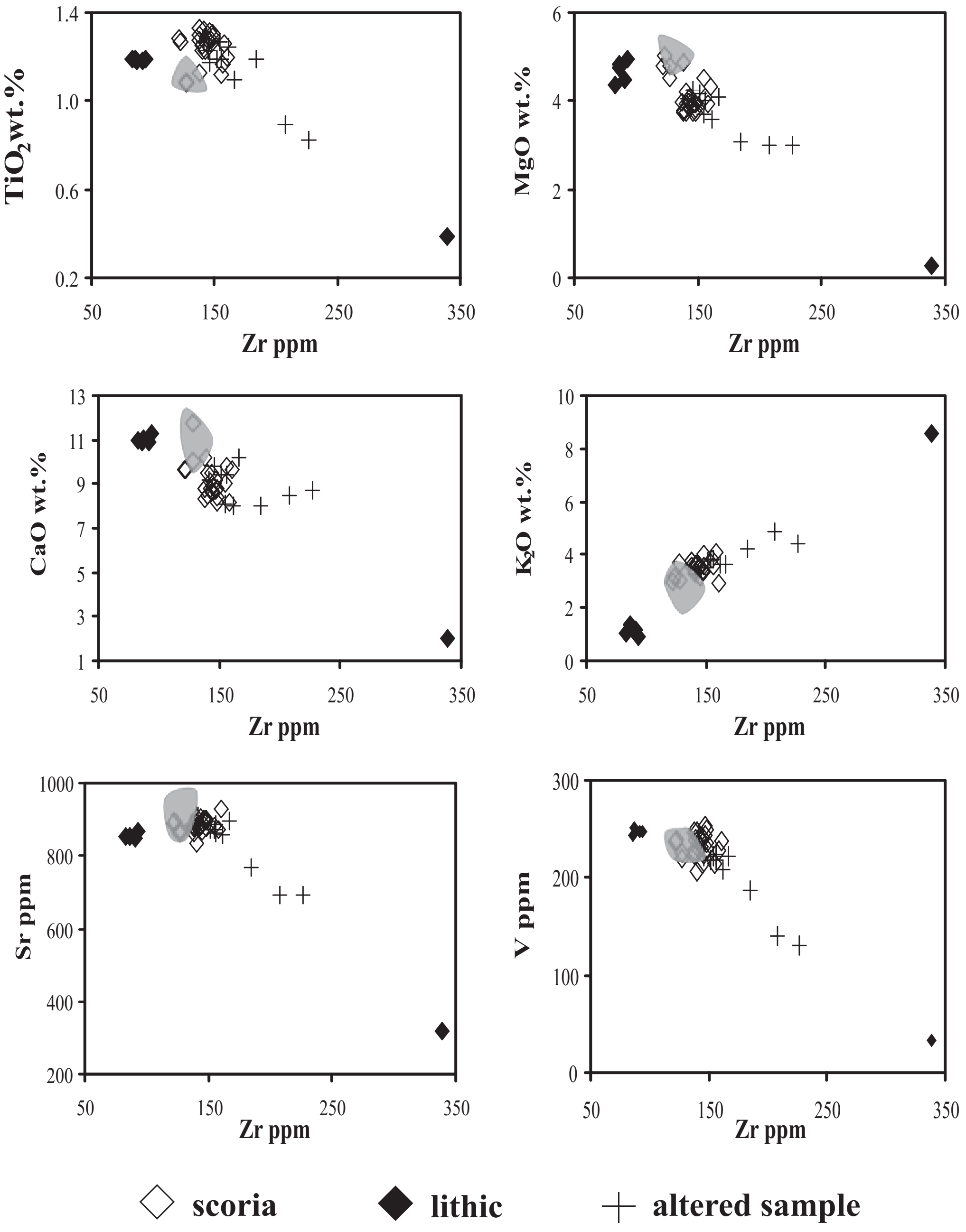


Fig. 9 – Selected major- and trace elements binary variation diagrams for the analyzed Fiumicello samples. Empty and full diamonds are used for juvenile scoria samples and lithic samples, respectively. Crosses are used to mark altered samples (see text). Shaded grey areas represent the compositional field of Fiumicello iuvenile samples taken from the literature (Di Girolamo and Rolandi, 1979; Di Girolamo et al., 1984; Pappalardo et al., 1999; De Astis et al., 2004).

the collected iuvenile samples (Fig. 9). The observed variations could be related to fractional crystallization processes, involving clinopyroxene (CaO, MgO and Sc decreases), Ca-rich plagioclase (CaO and Sr decrease), magnetite (decreasing of TiO_2 and Fe_2O_3) and olivine (MgO decrease) as the main fractionating phases.

A selection of samples has been chosen for further trace element analyses, determined by ICP-MS at the CRPG of Nancy, France. Absolute abundances have been normalized to chondritic and primitive mantle estimates values (Sun and McDonough, 1989) and then plotted on Fig. 10. For a comparison, the pattern relative to the least evolved Fiumicello iuvenile sample available in the literature [Pro 4/3a from De Astis et al. (2004)] is shown. The observed patterns are surely affected by fractionation processes (as expected for such non-primitive compositions), but still display the main characteristics of Campi Flegrei most basic products (e.g., D'Antonio et al., 1999), namely LREE enrichment (with respect to HREE; $(La/Yb)_n$ ~13), high LILE/HFSE ratios (e.g., Ba/Zr ~12) and evident Ta, Nb, Zr and Ti troughs (Fig. 10).

Mineral chemistry

Mineral and glass phases occurring within the collected iuvenile Fiumicello samples were analyzed by electron microprobe at the CNR-CSEAQ of Roma, Italy. Representative analyses are summarized in tables 2-5 and briefly discussed below.

Olivine. Olivine crystals show little chemical variation, with Fo contents spanning a very narrow range (Fo_{83-81}), both in the core and in the rim of the analyzed crystals (table 2).

Clinopyroxene. All the clinopyroxenes show a salitic composition, with a single exception (diopside). The observed compositions are very constant (typically within the ranges $Wo_{50-47}En_{41-37}Fs_{15-12}$ for the salitic crystals) with no zonation observed within each individual (table 3).

Plagioclase. Also plagioclase show a constant composition, with An contents characterized only by slight variations, from 89 to 82% (bytownite; table 4).

Glass. With the exception of rather higher Al and K and lower Ca and Mg contents, glass compositions are very similar to those of the host rock (table 5). Coexisting olivine-glass geothermometers, performed according to the method of Roeder and Emslie (1970), gave temperature estimates comprised between 1000 and 1100° C.

Mass-balance calculations

The existence of a genetic link between the analyzed samples, proposed on the basis of the linear trends of variation and REE plots, has been quantitatively tested by means of mass-balance calculations, according to the software of Stormer and Nicholls (1978).

The modellization of the transition between the least and the most evolved iuvenile samples could not be performed because all the samples representing more evolved compositions (i.e., FAM1, FAM3 and FAM13) have probably been affected by alteration processes, given their high LOI and normative qz or hy contents (see table 1). Their compositions, therefore, is unlikely to represent primary concentrations. Satisfactory results (R^2 ~0.3) have been obtained for the modellization of a shorter differentiation step, namely the transition from shoshonitic basalts (sample FCN1) to shoshonites (the sample FTR2), resulting from a fractionation of ~25% of an assemblage made of olivine (1%), salitic clinopyroxene (56%), bytownitic plagioclase (40%), magnetite (1%) and apatite (2%). These results (summarized in table 6) are in substantial agreement with those obtained by trace element modellizations, performed using Rayleigh's fractional crystallization equation (i.e., $C_l/C_0 = F^{(D-1)}$). Calculated C_l values (table 6) were then compared with observed C_l values (i.e., the trace-element concentrations measured within the most evolved term of the considered fractionation step), yielding a quite good correspondence between the two. A similar good correspondence could be observed between F values calculated by means of major element modellizations (i.e., ~74%) and F values calculated by resolving Rayleigh's equation for the most incompatible element of the proposed transition (~73%; see table 6).

Given the "non-primitive" character of the studied samples, an hypothetical parental magma

TABLE 1 – *Major elements (wt.%). LOI (wt.%). trace elements (ppm). and CIPW norm of the Fiumicello samples. by XRF for all the samples except FF2 and FAM5. for which trace elements and REE were*

Sample	FF1	FF2	FF3	FF4	FF5	FF6	FCN1	FCN2	FCN3	FCC	FAM1	FAM2	FAM3	FAM4	FAM5	FAM6	FAM7
Location			Punta Pioppeto					Punta Ottimo		Ciraccio				Acquamorta			
type	l	l	l	l	l	l	s	s	s	s	s	s	s	s	s	s	s
SiO_2	49.94	50.14	50.35	60.50	50.40	49.97	50.93	51.64	52.70	51.42	57.51	52.75	56.42	52.25	52.58	52.72	52.88
TiO_2	1.19	1.19	1.19	0.39	1.18	1.19	1.08	1.09	1.12	1.12	0.82	1.10	0.89	1.18	1.17	1.19	1.19
Al_2O_3	16.47	16.95	16.31	19.41	16.59	16.66	15.42	15.92	15.91	15.89	15.49	15.89	15.84	16.00	15.85	16.01	15.88
Fe_2O_3tot	9.88	9.95	9.98	3.33	9.84	10.23	9.29	9.36	9.58	9.57	7.33	9.40	7.80	9.84	9.77	9.90	9.89
MnO	0.14	0.15	0.15	0.15	0.15	0.15	0.14	0.14	0.15	0.14	0.14	0.15	0.14	0.15	0.15	0.15	0.15
MgO	4.83	4.35	4.75	0.28	4.47	4.95	4.77	4.50	4.51	4.88	3.00	4.07	2.99	4.24	4.10	4.16	4.00
CaO	11.08	10.94	10.86	2.02	10.87	11.31	11.74	10.04	9.04	10.22	8.68	10.22	8.45	9.77	9.78	9.39	9.40
Na_2O	4.78	4.92	4.87	5.28	4.97	4.27	3.26	3.33	2.90	2.92	2.40	2.45	2.40	2.76	2.66	2.44	2.45
K_2O	1.34	1.06	1.21	8.55	1.17	0.91	3.07	3.68	3.82	3.55	4.40	3.65	4.84	3.49	3.60	3.76	3.82
P_2O_5	0.37	0.35	0.34	0.08	0.35	0.35	0.30	0.30	0.29	0.29	0.22	0.32	0.22	0.31	0.34	0.28	0.33
LOI	1.42	1.36	1.59	0.31	1.39	3.73	2.82	1.38	2.06	1.20	8.48	4.53	7.31	3.47	3.68	4.13	4.42
Zn	62	73	65	64	63	68	76	68	23	66	83	83	83	77	66	79	77
Ni	20	24	19	3	21	28	33	34	33	38	31	37	29	30	28	28	29
Rb	30	53	40	234	48	58	123	130	151	154	166	135	167	138	129	135	135
Sr	855	853	855	317	848	865	873	895	881	879	694	895	694	892	819	874	862
Y	23	25	24	40	23	23	21	25	30	27	37	30	32	24	24	31	30
Zr	87	83	86	339	91	94	128	145	155	138	227	167	208	146	144	151	156
Nb	20	18	18	55	21	20	19	19	19	19	25	22	25	16	18	19	17
Sc	24	n.d.	27	2	25	26	30	26	20	26	16	23	18	23	23	23	22
V	250	n.d.	244	33	247	247	225	227	215	225	131	222	140	223	207	219	218
Cr	b.d.l.	n.d.	7	b.d.l.	b.d.l.	b.d.l.	b.d.l.	16	b.d.l.	b.d.l.	12	b.d.l.	b.d.l.	b.d.l.	14	b.d.l.	b.d.l.
Cu	59	n.d.	56	n.d.	51	39	70	65	68	72	37	59	38	69	51	51	60
Ba	1223	n.d.	1215	69	1202	1243	1107	1086	1106	1099	931	1164	953	1165	1048	1180	1169
Pb								16							17		
Hf								3.4							3.4		
Ta								1.1							1.1		
Th								9.3							10.6		
U								2.8							3.0		
La								35							38		
Ce								73							75		
Pr								9.0							9.3		
Nd								36							37		
Sm								7.7							7.7		
Eu								2.2							2.1		
Gd								6.5							6.4		
Tb								0.9							0.9		
Dy								4.8							4.8		
Ho								0.8							0.8		
Er								2.2							2.2		
Tm								0.3							0.3		
Yb								1.9							1.9		
Lu								0.3							0.3		
K_2O/Na_2O	0.28	0.21	0.25	1.62	0.24	0.21	0.94	1.11	1.31	1.22	1.83	1.49	2.01	1.26	1.35	1.54	1.56

Major elements concentrations were recalculated to LOI-free basis. Major elements and trace elements were obtained analyzed by ICP-MS. s = scoria clast; l = lithic clast; b.d.l. = below detection limit; n.d. = not detected.

FAM9	FAM10	FAM11	FAM12	FAM13	FAM14	FAM15	FAM16	FAM17	FAM18	FAM19	FVF1	FVF2	FTR1	FTR2	FTR3	FTR4	FTR5	FTR6
Acquamorta											Marina di Vitafumo		Torregaveta					
s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s	s
52.72	52.12	52.29	53.05	54.64	53.63	52.68	53.10	53.08	52.71	53.78	52.24	52.56	52.72	52.66	52.66	52.55	52.73	52.59
1.31	1.28	1.30	1.33	1.19	1.27	1.28	1.29	1.26	1.27	1.24	1.23	1.27	1.23	1.23	1.28	1.30	1.32	1.26
16.21	16.26	16.15	15.65	16.10	16.10	16.13	16.32	15.96	15.91	16.35	15.94	15.84	16.10	15.49	15.98	15.85	15.90	16.14
10.64	10.48	10.66	10.85	9.74	10.42	10.56	10.63	10.39	10.48	10.27	10.20	10.51	10.21	10.24	10.51	10.62	10.80	10.42
0.15	0.15	0.15	0.15	0.16	0.16	0.15	0.15	0.16	0.15	0.16	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.16
3.76	3.92	3.81	3.74	3.07	3.69	3.84	3.74	3.93	3.99	3.59	4.06	3.99	4.01	3.74	3.92	3.78	3.92	3.95
8.73	9.15	8.80	8.29	7.98	8.05	8.64	8.20	8.13	8.81	8.03	9.10	8.79	8.90	8.45	8.63	8.78	8.45	8.40
2.78	2.94	3.13	2.82	2.63	2.53	2.93	2.74	2.71	2.73	2.64	3.17	2.80	2.85	4.30	3.05	3.10	2.76	2.77
3.37	3.37	3.38	3.80	4.19	3.86	3.50	3.56	4.09	3.67	3.66	3.62	3.76	3.54	3.45	3.53	3.57	3.67	4.01
0.31	0.34	0.32	0.32	0.31	0.29	0.29	0.27	0.29	0.30	0.26	0.30	0.32	0.30	0.30	0.30	0.29	0.31	0.30
4.15	3.65	3.40	6.06	6.68	3.73	3.25	3.81	2.74	2.84	3.50	1.49	2.36	2.06	4.64	3.27	3.40	3.44	2.80
87	78	80	81	90	81	81	83	80	83	86	76	79	75	75	78	79	75	80
20	25	21	21	24	25	25	22	24	25	24	27	27	26	26	23	23	25	25
134	133	141	128	150	148	147	140	141	145	142	166	150	154	154	150	152	144	138
901	901	903	864	769	872	884	878	870	882	856	878	887	866	832	889	883	880	895
26	32	29	28	36	33	27	33	27	33	36	30	28	29	28	31	26	26	25
146	147	148	138	185	154	144	148	158	143	162	142	138	145	140	145	138	141	148
18	18	18	20	22	18	17	20	18	21	19	19	17	17	18	22	19	17	22
23	22	20	21	22	21	23	20	20	25	22	19	30	22	21	23	26	20	23
243	252	249	239	188	223	231	230	227	239	208	242	247	215	207	224	228	229	237
b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	10	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.
45	45	44	44	45	44	46	48	51	47	39	53	51	57	48	47	47	52	50
1306	1304	1311	1227	1199	1301	1264	1214	1278	1256	1184	1270	1239	1236	1183	1281	1231	1231	1297
1.21	1.14	1.08	1.34	1.60	1.53	1.19	1.30	1.51	1.34	1.39	1.14	1.34	1.24	0.80	1.16	1.15	1.33	1.44

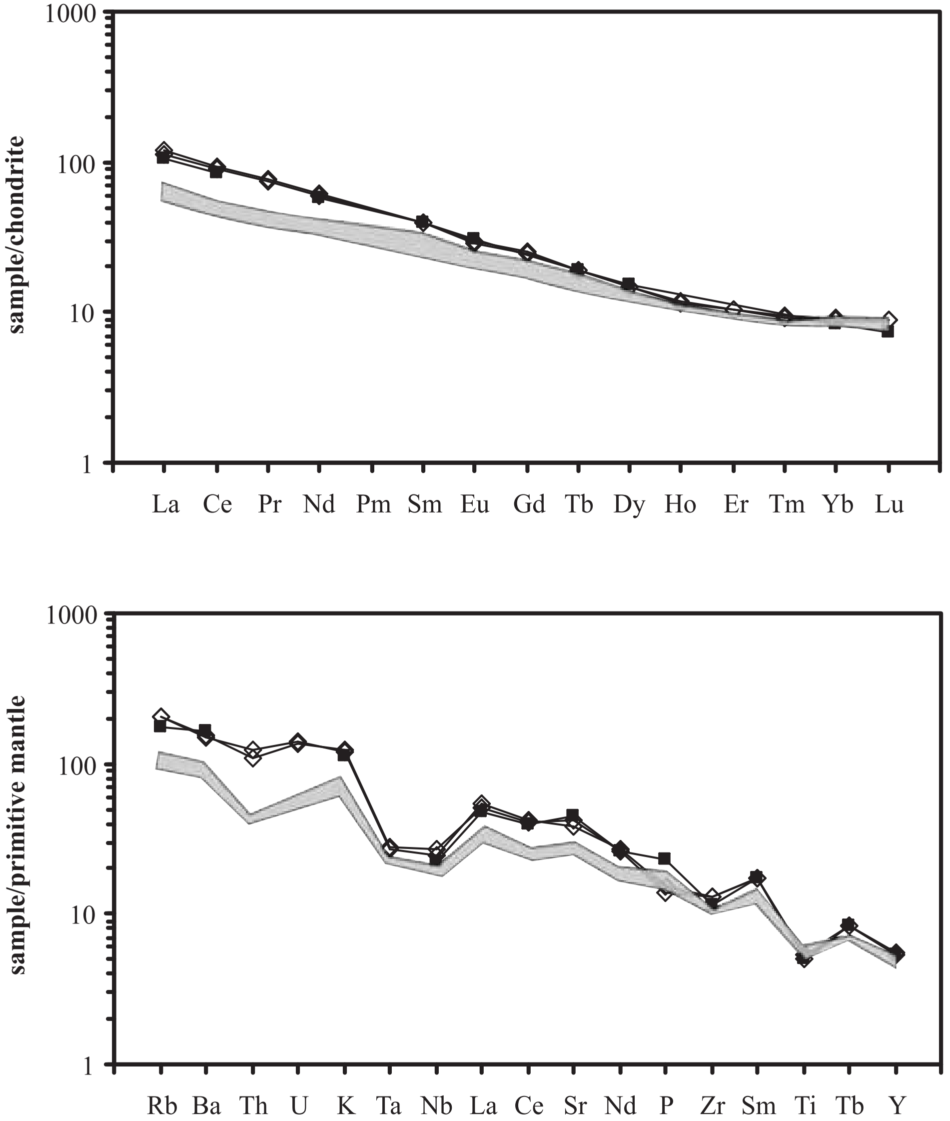


Fig. 10 – Chondrite- and primitive- mantle normalized diagrams for some analyzed Fiumicello samples (FCN2 and FAM5, open diamonds). Black squares refer to Fiumicello scoria sample Pro4/3a from De Astis et al. (2004). Shaded grey areas represent the patterns of Campi Flegrei most basic products [data from D'Antonio et al. (1999)]. Normalization values from Sun and McDonough (1989).

TABLE 2 – *Representative electron microprobe analyses of olivines of the Fiumicello juvenile products. Fo % = forsterite wt.%.*

sample	FAM5	FAM10	FAM10
point	core	rim	core
SiO_2	39.84	39.08	39.01
MgO	44.25	43.06	43.39
CaO	0.38	0.34	0.36
MnO	0.43	0.34	0.29
FeO	16.03	18.33	17.96
Na_2O	0.02	0.02	0.03
Total	100.99	101.27	101.09
Fo%	83.11	80.72	81.15

from the available dataset of Campi Flegrei less evolved rocks [namely, the picritic basalt sample APR18 of D'Antonio et al. (1999)] was chosen in order to perform a modellization of the transition from this sample to the least evolved Fiumicello sample (i.e., FCN1). The resulting model requires a fractionation of ~36% of an assemblage made up of olivine (~42%), diopsidic clinopyroxene (~26%) and bytownitic plagioclase (32%). These results, even if barely acceptable on the basis of R^2 values (~0.9), are in quite good agreement with trace-element modellizations. The resulting F values (59% or 72%, respectively assuming Nb or Zr as the most incompatible element), in fact, are quite consistent with the value of ~64% coming from the above mentioned major elements modellizations (see table 7). Successively, Rayleigh's equation was used to obtain calculated C_l values relatively to the transition from picritic basalt to shoshonitic basalt, as illustrated above for the transition from shoshonitic basalt to shoshonite. The evident differences between observed and calculated C_l values (table 7) are likely to reflect the choice of sample which can not be taken as representative of a comagmatic picritic parental magma relatively to the studied samples.

Geochemical stratigraphy

For each of the studied stratigraphic sections binary diagrams showing the variation of chemical parameters versus the variation of relative stratigraphic height (h%) were drawn. These

TABLE 3 – *Representative electron microprobe analyses of clinopyroxenes of the Fiumicello juvenile products. En % = enstatite wt.%; Wo % = wollastonite wt.%; Fs % = ferrosilite wt.%.*

sample	FAM5	FAM5	FAM5	FAM5	FAM5	FAM10	FAM10
point	core	rim	core	core	core	core	core
SiO_2	46.67	51.25	50.63	46.11	49.08	47.81	48.64
TiO_2	1.81	0.70	0.60	1.96	1.11	0.93	1.10
Al_2O_3	8.58	4.01	3.25	8.76	5.20	6.07	5.43
Cr_2O_3	0.04	0.01	0.06	0.04	0.01	–	–
MgO	12.84	16.03	13.06	12.84	14.44	12.92	14.28
CaO	23.62	23.31	23.01	23.49	23.05	23.14	23.07
MnO	0.10	0.13	0.26	0.14	0.20	0.22	0.12
FeO	7.28	5.42	9.04	7.11	7.52	8.92	7.21
Na_2O	0.26	0.19	0.61	0.27	0.22	0.25	0.23
Total	101.22	101.06	100.52	100.72	100.84	100.25	100.11
En %	37.8	44.6	37.5	38.0	40.9	37.2	40.8
Wo %	50.0	46.7	47.5	50.0	46.9	48.0	47.4
Fs %	12.2	8.7	15.0	12.0	12.3	14.8	11.8

TABLE 4 – *Representative electron microprobe analyses of plagioclases of the Fiumicello juvenile products. An % = anorthite wt.%; Or % = orthoclase wt.%; Ab % = albite wt.%.*

sample	FAM5	FAM5	FAM5	FAM10	FAM10	FAM10
point	rim	core	core	rim	core	rim
SiO_2	45.61	45.71	47.14	45.27	46.60	46.10
Al_2O_3	33.74	34.29	33.42	34.25	32.35	34.06
CaO	18.47	18.27	17.21	18.26	16.79	18.13
Fe_2O_3	0.72	0.60	0.74	0.64	1.54	0.81
Na_2O	1.15	1.12	1.66	1.14	1.57	1.32
K_2O	0.18	0.21	0.28	0.19	0.67	0.26
Total	99.93	100.29	100.58	99.88	99.97	100.78
An %	88.9	89.0	83.8	88.9	82.2	87.1
Or %	1.1	1.2	1.6	1.1	3.9	1.5
Ab %	10.0	9.8	14.6	10.1	13.9	11.4

plots have been used to evaluate the existence of potential geochemical zoning within the products of the Fiumicello eruption.

As a whole, compositions of the analyzed samples seem to be quite constant for the whole column length, with a more pronounced degree of variability regarding only SiO_2 and Na_2O. These variations, however, are likely to be strongly affected by the aforementioned alteration processes which could have deeply modified SiO_2 and Na_2O original concentration values. The samples of the Acquamorta section seem to display a pattern of slight decrease of the degree of differentiation with increasing stratigraphic height (Fig. 11), with two of the lowermost samples clearly showing the most evolved compositions of the whole sequence (e.g., MgO ~3.0%, CaO ~84.5%, Zr ~200 ppm). With very few exceptions, all the other samples collected from this section show very homogeneous compositions. The stratigraphic sections of Torregaveta and Marina di Vitafumo do not show similar vertical patterns. A vertical chemical zoning exactly opposite to that observed in the Acquamorta section characterizes the Punta Ottimo section, with the topmost FCN3 sample being also the most evolved sample of the sequence (e.g., SiO_2 52.7%, CaO 9.04%, Zr 155 ppm, where the other samples have SiO_2 50.9-51.6%, CaO 10.0-11.7%, Zr 128 ppm).

DISCUSSION AND CONCLUSIONS

The results shown in this study contributed to shed light on the main volcanological and geochemical characteristics of the deposits of the Fiumicello eruption.

The analysis of the volcanological and stratigraphical features, together with the interpretation of the recognized lithofacies, allowed the recognition of two distinctive eruptive phases. An almost purely magmatic phase, involving a

TABLE 5 – *Representative electron microprobe analyses of glasses in the Fiumicello juvenile products.*

sample	FAM5	FAM10	FAM10
SiO_2	48.92	48.57	50.10
TiO_2	1.24	1.40	1.45
Al_2O_3	17.20	17.34	16.87
MgO	2.79	4.23	3.15
CaO	7.05	8.93	7.82
MnO	0.18	0.12	0.20
FeO	8.90	9.28	9.87
Na_2O	3.02	2.91	3.09
K_2O	4.30	4.91	5.58
Total	93.59	97.67	98.14

TABLE 6 – *Results of major- and trace elements mass-balance calculations for the analyzed juvenile Fiumicello products. Trace elements modellizations were performed resolving Rayleigh's fractional cristallization equation for C_l (i.e., $C^l = C_0 * F^{(D-1)}$). In this model, C_l is the concentration of a trace element within the most evolved term of the transition, C_0 is the concentration of a trace element within the least evolved term of the transition, F is the fraction of residual liquid, derived from major-elements mass-balance calculations, and D is the bulk distribution coefficient for a specific trace element. D values were calculated ($D = \sum X_i * Kd_i$) using X values (i.e., the fraction of each fractionating phase within the fractionation assemblage) obtained by major-elements mass-balance calculations, and Kd values (i.e., the partition coefficient relative to each fractionating phase) taken from the available literature for Campi Flegrei products (Villemant, 1988; Ricci, 2000; Morra et al., 2003). R^2 = sum of square residuals; cumulate % = wt.% of fractionating cumulate (referred to starting magma); F % = wt.% of residual liquid; phases % = wt.% of fractionating phases; C_0 = trace element concentration within the least evolved magma; $C_l$obs = observed trace element concentration within the most evolved magma; $C_l$calc = calculated trace element concentration within the most evolved magma. F(Y) is the wt.% of residual liquid obtained from trace element modellizations by assuming Y as the most incompatible element and therefore resolving Rayleigh's equation and therefore assuming for it a D value of 0 and using for C_l and C_0 the concentration values of Y within the most evolved and the least evolved term of the transition. Analyses of magnetite and apatite from Fedele (2006) and from Fulignati et al. (2004), respectively. See text for further explanations.*

	FCN1	FTR2
SiO_2	50.93	52.66
TiO_2	1.08	1.23
Al_2O_3	15.42	15.49
Fe_2O_3	9.29	10.24
MnO	0.14	0.15
MgO	4.77	3.74
CaO	11.74	8.45
Na_2O	3.26	4.30
K_2O	3.07	3.45
P_2O_5	0.30	0.30
R^2	0.31	
cumulate %	25.6	
F %	74.4	
phases %		
Ol	1.3	
Cpx	55.6	
Pl	39.7	
Mt	1.0	
Ap	2.4	

	FCN1	FTR2	
	C_0	$C_l$obs	$C_l$calc
Zr	128	140	150
Ni	33	26	23
Rb	123	154	148
Sr	873	832	895
Y	21	28	24
Nb	19	18	25
Sc	30	21	14
V	225	207	299
Ba	1107	1183	1206

$F(Y) = C_0/C_l = 73\%$

TABLE 7 – *Results of major- and trace element modellization of the transition from a Campi Flegrei picritic basalt [sample APR18 of D'Antonio et al. (1999)] to a shoshonitic basalt sample of the Fiumicello formation. Trace elements modellizations were performed as described in table 6 caption. R^2 = sum of square residuals; cumulate % = wt.% of fractionating cumulate (referred to starting magma); F % = wt.% of residual liquid; phases % = wt.% of fractionating phases; C_0 = trace element concentration within the least evolved magma; $C_l$obs = observed trace element concentration within the most evolved magma; $C_l$calc = calculated trace element concentration within the most evolved magma; F(Zr) = percentage of residual liquid obtained assuming Zr as the most incompatible element (see table 6 captions); F(Nb) = percentage of residual liquid obtained assuming Nb as the most incompatible element (see table 6 captions). Clinopyroxene analysis from D'Antonio et al. (1999). See text for further explanations.*

	APR18	FCN1
SiO_2	48.98	50.93
TiO_2	1.10	1.08
Al_2O_3	14.17	15.42
Fe_2O_3	8.86	9.29
MnO	0.14	0.14
MgO	11.11	4.77
CaO	11.47	11.74
Na_2O	2.66	3.26
K_2O	1.25	3.07
P_2O_5	0.25	0.30
R^2	0.98	
cumulate %	36.2	
F %	63.8	
phases %		
Ol	41.7	
Cpx	25.8	
Pl	32.5	

	APR18	FCN1	
	C0	Clobs	Clcalc
Zr	92	128	108
Ni	233	33	126
Rb	39	123	47
Sr	439	873	476
Y	20	21	27
Nb	11	19	15
Sc	39	30	18
V	184	225	247
Ba	387	1107	421

F(Zr) = C_0/C_l = 72%

F(Nb) = C_0/C_l = 59%

very scarce magma/water interaction, is testified by the scoriaceous lapilli fallout deposits of the Monte di Procida outcrops. A second, frankly phreatomagmatic phase, involving high quantities of water, is testified by the cineritic deposits of the Procida outcrops and by the cineritic levels of the Monte di Procida outcrops. These two phases seem to have alternated very regularly during the very first stages of the event, giving birth to the tight intercalation of their relative deposits observed in the Monte di Procida area. If this is taken for valid, the rough alternation of scoriaceous lapilli and cineritic levels observed in the section of Punta Ottimo could represent an evidence of the occurrence of the magmatic products also in the proximal deposits. Alternatively, the eruption could have started as a purely magmatic event, and only successively the conditions for an effective magma/water interaction would have been reached, thus allowing the development of the

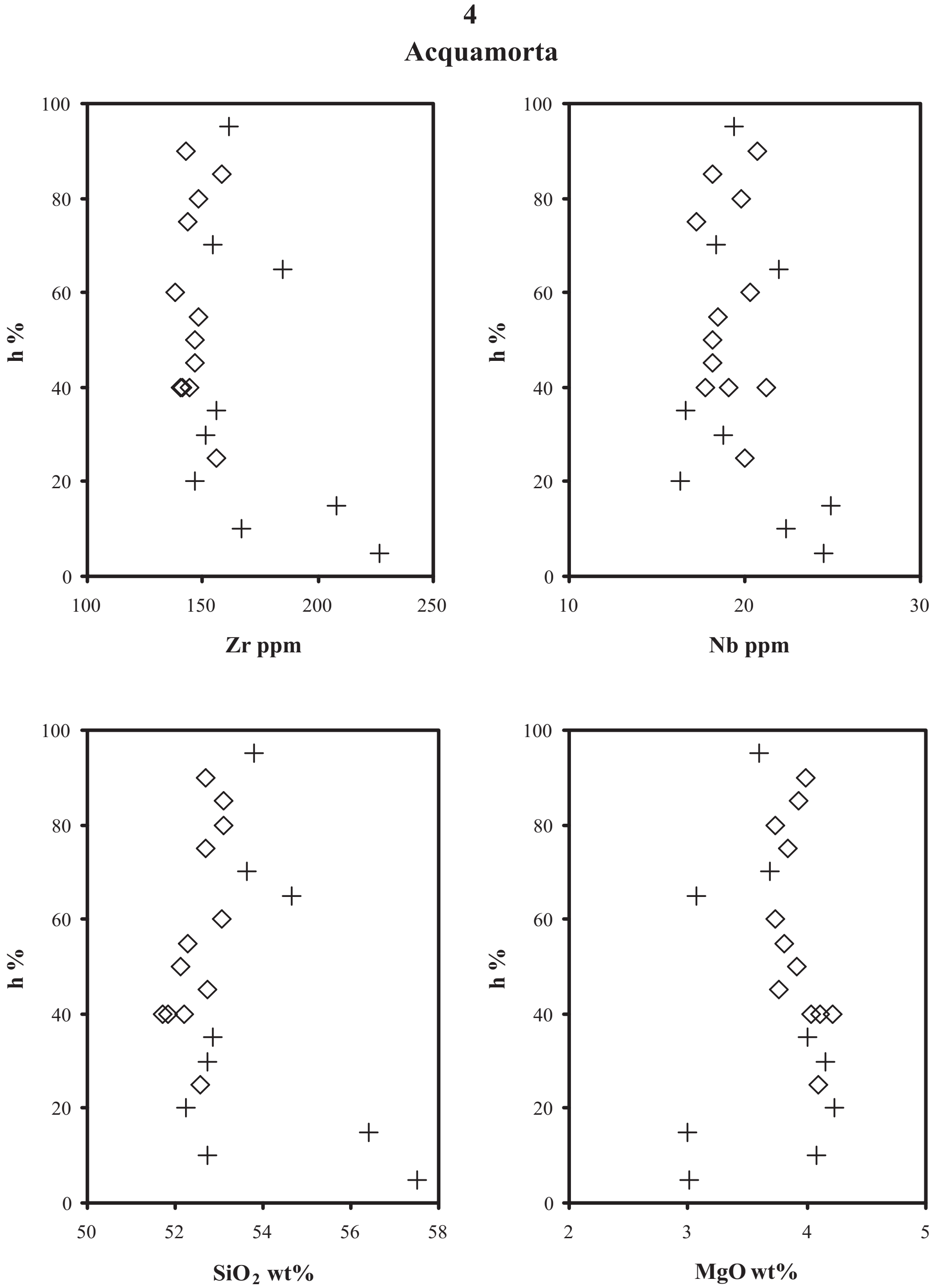


Fig. 11 – Selected major- and trace element concentrations vs. relative stratigraphic height (h%) binary plots for the analyzed juvenile samples of the Fiumicello deposit studied at the Acquamorta locality. Symbols as in figure 10.

phreatomagmatic phases of the event. In this case, it should be considered that the absence of the products of the magmatic phases in the proximal outcrops is only a consequence of their complete obliteration (due to erosion or covering) by the successive emplacement of the deposits of the phreatomagmatic phases.

The mechanisms of emplacement of the Fiumicello deposits seem to be attributable to both low-energy pyroclastic flows (for the deposits of the proximal outcrops), and to fallout processes related to a phase of sustained-column activity (the deposits of the distal outcrops). The height of the sustained column is likely to have been between 6.8 and 13.8 km, while the minimum volume of fallout products was assessed to be of ~0.13 km^3. An important role in the deposition of the pyroclasts of the fallout phase must have been played by the local winds, as indicated by the very asymmetrical dispersion pattern of the proposed isopach and isopleth maps and by the calculated wind velocities, in the range of 20-30 m/s.

The volcanological features of Fiumicello eruption largely resemble those of many other monogenetic edifices of Campi Flegrei (e.g., Astroni: Rosi and Sbrana, 1987; Agnano-Monte Spina: Rosi and Sbrana, 1987; de Vita et al., 1999; Averno: Rosi and Sbrana, 1987; Mastrolorenzo, 1994). The volcanological evolution of these events, in fact, are characterized by both phreatomagmatic and fallout phases, exactly as for the Fiumicello eruption. The calculated volume of erupted magma seems to be also quite similar, given, for example, the values of ~0.05 km^3 (Rosi and Sbrana, 1987) and of ~1.2 km^3 (de Vita et al., 1999) reported for the Agnano-Monte Spina eruption. All these similarities make the Fiumicello eruption a good "type-event" for the Campi Flegrei area, both for the volcanological evolution and for the magnitude of the event. Moreover, it appears that changes in the degree of magma/water interaction have played a major role during the whole volcanological history of the district, given that all these similar events belong to different phases of the Campi Flegrei activity (i.e., pre-CI for Fiumicello, post-NYT for Astroni, Agnano-Monte Spina and Averno).

The iuvenile products of the Fiumicello eruption are amongst the least evolved products of the entire Campi Flegrei district, ranging from shoshonitic basalts to latites. Notwithstanding this, they do not show typical compositions of primitive magmas, as it is evident also from the results of our modelling of evolutionary processes, which linked them to primitive picritic magmas by a 35% fractionation of an assemblage made of olivine, plagioclase and clinopyroxene (in decreasing order of abundance). The very limited chemical variability observed within the juvenile samples (i.e., from shoshonitic basalts to latites) has also been modelled, involving a fractionation of 25% of a gabbroic assemblage made of clinopyroxene (~56%), plagioclase (~40%) plus accessory olivine, magnetite and apatite.

Looking at figures 8 and 9, it is interesting to note that the bulk composition of the samples of this study is somewhat different from that of the Fiumicello samples of the existing literature. This could be partly due to the very few bibliographic data, with only 11 available juvenile analyses. Anyway, it is to note that these data refer mainly to samples collected on Procida Island, while samples form this study are coming predominantly from "continental" outcrops. Literature samples coming from Procida are potentially slightly less evolved, as it is also evident from chondrite- and primitive mantle-normalized diagrams shown in Fig. 10, were the sample taken from the literature is potentially slightly less fractionated than samples from this study (e.g., slightly lower normalized values, absence of P negative peak possibly linked to apatite fractionation). Moreover, the samples from this study which more evidently resemble those of the literature are those coming from Procida outcrops. Therefore, the different chemical character of "continental" and "insular" deposits could be interpreted to reflect specific characteristics of the feeding magma.

As regards the chemical variations observed within each stratigraphic section, only the Acquamorta section should be considered as indicative of effective vertical chemical zonations within the Fiumicello deposits. The other studied sections have not been sampled in similar detail and thus the vertical geochemical patterns observed within them could not be considered reliable on a statistical ground. Moreover, some of those sections have not been sampled for their whole length, like the Punta Ottimo section, in which the last two meters of the section were not directly accessible to sampling. Therefore, the Acquamorta section should be taken as a type-section of the Fiumicello deposits and, consequently, the vertical compositional variations of the products observed within that section, although not too evident, should be considered as representative of a primary feature of the deposit. The lack of similar evidences in the other sections, or even the existence of evidences of an opposite geochemical zoning within the Punta Ottimo section, should be ascribed, therefore, to an incomplete sampling.

If the geochemical zoning observed within the products of the Acquamorta section is taken as a main feature of the Fiumicello deposits, it is necessary to assume that the magma reservoir feeding the Fiumicello eruption must have attained the conditions for density stratification of magmas. In such a context, the lighter and more evolved magmas of the shallowest parts of the reservoir would have fed the first stages of the eruption, while the deepest, densest and less evolved batches would have been tapped only by the final phases of activity. The existence of a density stratified magma chamber would be also consistent with the observed compositional differences between "continental" and "insular" Fiumicello samples. In fact, as proposed above, "continental" Fiumicello samples may be considered to represent the product of the first, mainly magmatic phase of the eruption, while "insular" Fiumicello deposit represent the products of a successive phreatomagmatic phase. In this framework, the previously discussed geochemical vertical variation towards less evolved lithotypes, observed within the products of the fallout phase at the Acquamorta locality, is still recognizable in the transition from the more evolved "continental" deposits of the magmatic fallout phase to the less evolved "insular" deposits of the following phreatomagmatic phase.

The occurrence of chemical zonation patterns within Campi Flegrei products has already been ascribed to the existence of similar stratified structures (e.g., Di Girolamo, 1970; Melluso et al., 1995; Civetta et al., 1997; de Vita et al., 1999; Pappalardo et al., 2002a). The frequent development of chemically-stratified magma chambers within the whole district may be interpreted as further evidence of the great complexity of phlegrean magmatic system, likely involving several

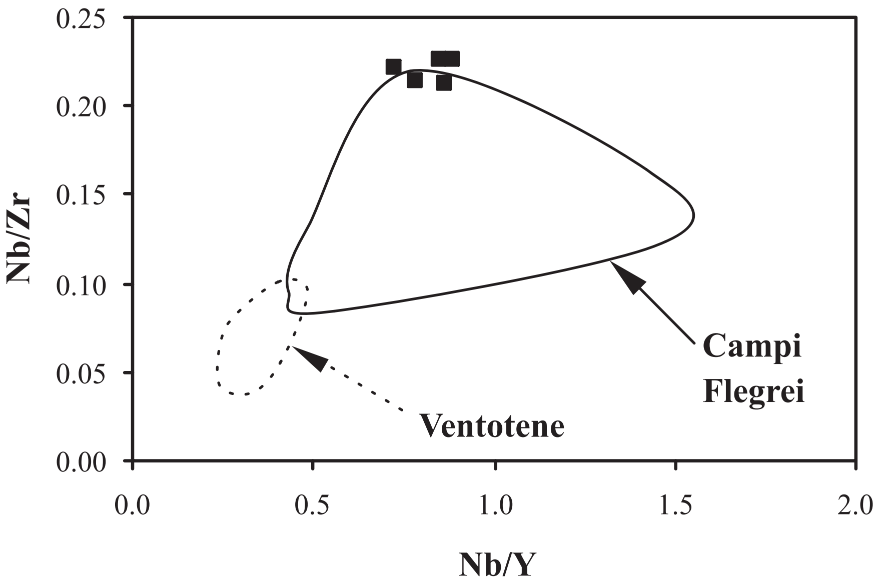


Fig. 12 – Nb/Zr vs. Nb/Y binary plot for the Fiumicello lithic samples (excluded FF4 trachytic sample) collected at the Punta Pioppeto locality. The two reported fields refer to the compositions of Ventotene and Campi Flegrei products with similar degree of differentiation [data from Beccaluva et al. (1991), D'Antonio and Di Girolamo (1994), D'Antonio et al. (1999), Pappalardo et al. (1999), Lustrino et al. (2002), De Astis et al. (2004)]. See text for further explanations.

individually-evolving magma chambers as already proposed by several authors (e.g., Beccaluva et al.,1990; D'Antonio et al., 1999; Pappalardo et al., 1999, 2002b; De Astis et al., 2004), mainly on isotopic grounds.

The unusual composition of the collected shoshonitic basalt lithic samples (i.e., FF1, FF2, FF3, FF5 and FF6), which yielded unusually low K_2O/Na_2O values (i.e., ~0.2), represents a scarcely documented topic within Campi Flegrei products of similar degree of differentiation. A more evident affinity exists, instead, with products of the activity of Ventotene, for which D'Antonio and Di Girolamo (1994) reported similar low K_2O/Na_2O values. However, the very different values of some incompatible elements ratios (e.g., Nb/Zr and Nb/Y) observed in these lithic samples (Nb/Zr ~0.73-0.89 and Nb/Y ~0.21-0.23) with respect to those typical of Ventotene products (i.e., Nb/Zr ~0.32-0.48 and Nb/Y ~0.05-0.09; D'Antonio and Di Girolamo, 1994) excludes the possibility to establish the existence of a magmatological link between the two groups of products. Other authors already pointed out such differences between *Neapolitan* products (i.e., rocks from Campi Flegrei and Somma-Vesuvio) and products from the nearby districts of the Pontine Islands, Roccamonfina and Ernici, attributing them to the existence of geochemical discontinuities within the mantle (e.g., Di Girolamo, 1987; Beccaluva et al., 1991). Successively, D'Antonio and Di Girolamo (1994) gave a further confirmation to this hypothesis on the basis of $^{87}Sr/^{86}Sr$ data, similarly suggesting the existence of such mantle discontinuities. The observed Nb/Zr and Nb/Y values of Punta Pioppeto shoshonitic basalt lithic samples (Fig. 12) are more akin to those depicting the field of the aforementioned *Neapolitan* district (respectively, ~0.6-1 and ~0.11-0.20; Beccaluva et al., 1991).

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