RESEARCH ARTICLE

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Volcanic hazard assessment at the restless Campi Flegrei caldera

Abstract Eruption forecasting and hazard assessments at the restless Campi Flegrei caldera, within the Neapolitan volcanic area, have been performed using stratigraphical, volcanological, structural and petrological data.

On the basis of the reconstructed variation of eruption magnitude through time, we hypothesize that the most probable maximum expected event is a medium-magnitude explosive eruption, fed by trachytic magma. Such an eruption could likely occur in the north-eastern sector of the caldera floor that is under a tensile stress regime, when the ongoing deformation will generate mechanical failure of the rocks. A vent could open also in the western sector, at the intersection of two fault systems contemporaneously activated, as happened in the last eruption at Monte Nuovo. The eruption could likely be preceded by precursors apparent to the population, such as ground deformation, seismicity and increase in gas emissions. It will probably alternate between magmatic and phreatomagmatic phases with the generation of tephra fallout, and dilute and turbulent pyroclastic currents. During and/or after the eruption, the re-mobilization of ash by likely heavy rains, could probably generate mud flows.

In order to perform a zoning of the territory in relation to the expected volcanic hazards, we have constructed a comprehensive hazard map. On this map are delimited (I) areas of variable probability of opening of a new vent, (II) areas which could be affected by variable load of fallout deposits, and (III) areas over which pyroclastic currents could flow. The areas in which a vent could likely open have been defined on the basis of the dynamics of the ongoing deformation of the caldera floor. To construct the fallout hazard map we have used the frequency of deposition of fallout beds thicker than 10 cm, the frequency of load on the ground by tephra fallout and the direction of dispersal axes of the deposits of the last 5 ka, and the limit load of collapse for the variable types of roof construction. The pyroclastic-current hazard map is based on the areal distribution and frequency of pyroclastic-current deposits of the last 5 ka.

Introduction

Eruption forecasting and volcanic hazard assessment (Sparks 2003) are essential for elaborating actions designated to mitigate volcanic risk. Many countries are in the process of preparing emergency plans in order to manage volcanic crises through the collaborative work of experts from different disciplines, such as volcanologists, civil authorities, civil defence officials, land managers, city-planners, sociologists and mass-media. Volcanic hazard assessment and volcanic risk mitigation are mandatory for any modern society, given that a large number of communities, including megacities, are growing around and upon active volcanoes. Naples, together with its surrounding towns, has been growing between the Campi Flegrei restless caldera and the Somma-Vesuvius complex (Orsi et al. 2003). This megacity is located on two active volcanoes and is close to a third active volcano (the island of Ischia). Being densely populated, Naples is one of the World's best examples of a high volcanic risk area.

The Campi Flegrei caldera (CFc), a nested and resurgent structure (Orsi et al. 1996, 1999a), is the largest volcano in the Phlegraean Volcanic District, which also includes the islands of Procida and Ischia (Fig. 1b). Its magmatic system is still active with the last eruption occurring in 1538 A.D. (Monte Nuovo; Di Vito et al. 1987), widespread fumaroles and hot springs activity (Allard et al. 1991), and the unrest episodes in the last 35 years, with a maximum net uplift of about 3.5 m in the Pozzuoli area (Orsi et al. 1999a and references therein). The volcanic hazard of the caldera is extremely high also because of its explosive character and the occurrence of high-magnitude eruptions. Close to 1.5 million people live within the caldera, with about 350,000 people living in its active portion. Due to the high volcanic hazard and the intense

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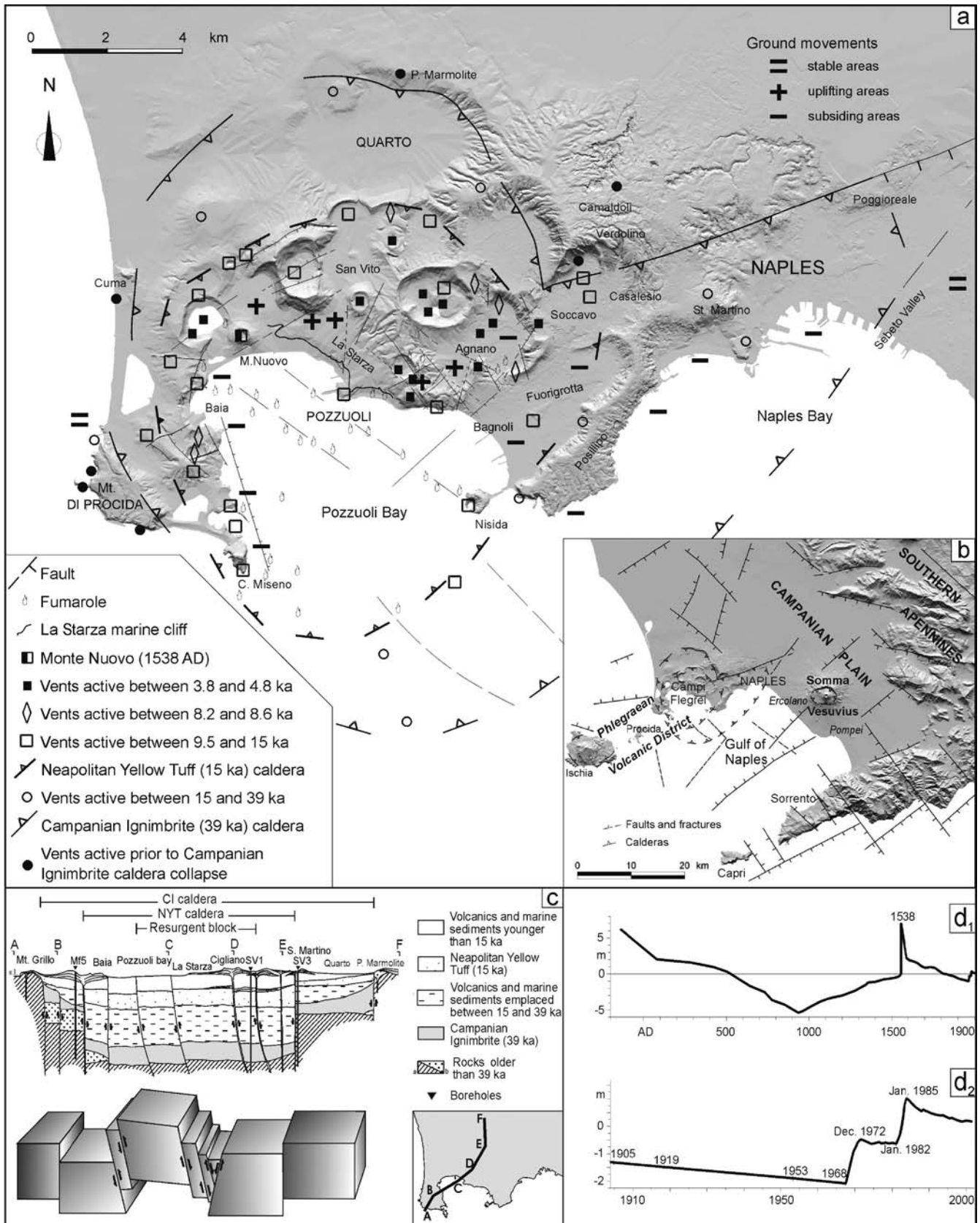Via Diocleziano 328, 80124 Napoli, Italy
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Fig. 1a–d (**a**) Structural sketch map of the Campi Flegrei caldera (modified after Wohletz et al. 1999). (**b**) Structural sketch map of the Campanian region including the Somma-Vesuvius volcano and the Phlegraean Volcanic District (Campi Flegrei, Procida and Ischia). (**c**) Geological cross section through the Campi Flegrei cal-dera and illustration of the proposed dynamic model (modified after Orsi et al. 1991, 1996). Vertical ground movement (**d₁**) at the Serapeo roman market and (**d₂**) at the most deformed benchmark of the levelling network in Pozzuoli (note different time scales)

urbanisation of both the active portion of the caldera and its surroundings, the volcanic risk is very high.

Two papers have been recently published on hazard assessment (Lirer et al. 2001) and long-term volcanic risk evaluation (Alberico et al. 2002) at the CFc. We firmly believe that a volcanic hazard assessment for each individual volcano has to be based on the entire set of available data on its past history and present state, and on the morphological characteristics of the surrounding territory. Therefore we have used all the geological, volcanological, structural and petrological data currently available, together with the results of stratigraphical and volcanological researches still in progress, in an attempt to forecast the most probable maximum expected eruption in case of renewal of volcanism in the next years or tens of years (short-mid term), assess the related volcanic hazards, and perform a zoning of the territory in relation to the expected hazards. We have also attempted to define the structural conditions that could allow an eruption to occur, and the areas within the caldera where a new vent is most likely to open.

A preliminary version of the results presented here was submitted in 1998 to the Italian Department for Civil Defence and adopted as the scientific basis for the development of an Emergency Plan.

Past behaviour and present state of the Campi Flegrei caldera

Volcanism and long-term deformation

Orsi et al. (1992, 1996), on the basis of the results of surface and subsurface geological investigations, and of geochronological and geophysical data, suggested that the CFc has been generated by at least two major collapses. Those collapses were related to the Campanian Ignimbrite (CI; 39 ka; Barberi et al. 1978; Fisher et al. 1993; Rosi et al. 1996, 1999; Civetta et al. 1997; De Vivo et al. 2001; Fedele et al. 2002, 2003; Pappalardo et al. 2002a) and Neapolitan Yellow Tuff (NYT; 15 ka; Orsi et al. 1992, 1995; Scarpati et al. 1993; Wohletz et al. 1995; Deino et al. 2004) eruptions, respectively (Fig. 1a). Large sectors of the structural boundary of both calderas resulted from partial reactivation of pre-existing faults generated by regional tectonism. After each caldera collapse, volcanism was restricted within the collapsed area. The whole structure is subsiding, while the central part of the NYT caldera is affected by resurgence occurring through a simple-shearing mechanism (Fig 1a, c; Orsi et al. 1991), which has disrupted its floor into several blocks. This long-term deformation has generated a net vertical uplift of about 90 m of the most uplifted block, which includes the La Starza marine terrace (Orsi et al. 1996).

Orsi et al. (1996) reconstructed the volcanic and deformational history of the caldera which was later detailed by Di Vito et al. (1999), Orsi et al. (1999a) and Isaia et al. (2004) (Fig. 2). Current stratigraphical and structural investigations have allowed us to identify four new erup-
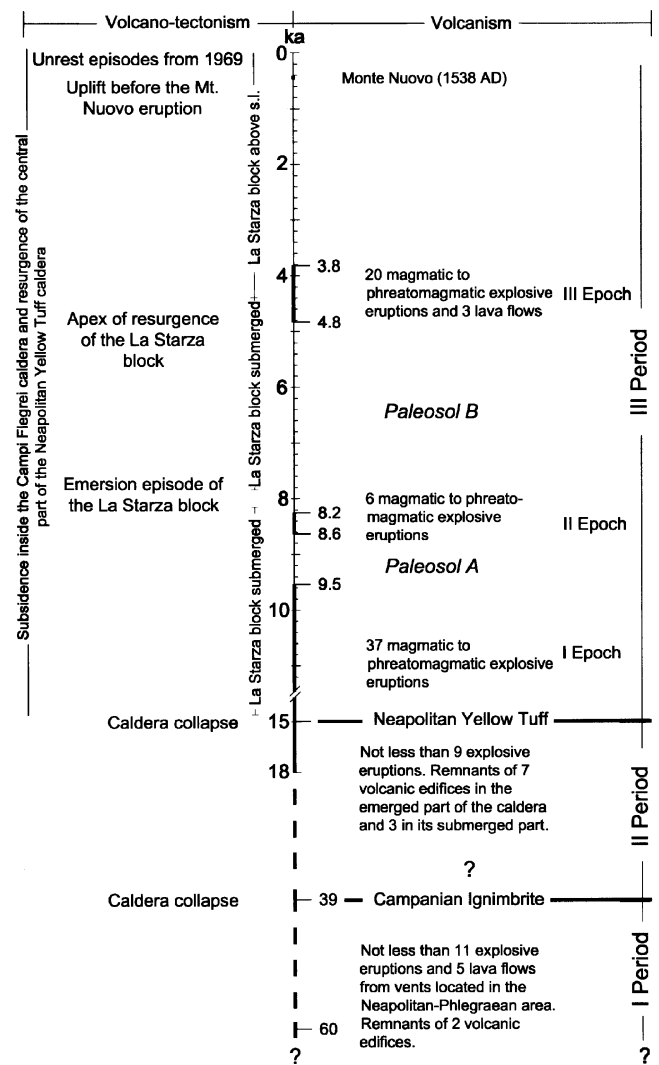

Fig. 2 Chronostratigraphy of the volcanic and deformational events of the Campi Flegrei caldera

tions. After the NYT eruption, volcanism was concentrated in three epochs of activity, alternating to periods of quiescence (Fig. 2). Volcanism and quiescence are strictly related to the deformation of the caldera. The areal distribution of the eruption vents in each epoch (Fig. 1a) is a good tracer of the active structures which have favoured magma upraise to surface through time. The great majority of the recognised eruptions (64 out of 67) were explosive, almost all characterised by alternating phreatomagmatic and magmatic explosions. We have reconstructed (Fig. 3) and will discuss in the following paragraphs the areas covered by the pyroclastic-fall and –current deposits of each explosive eruption. Assuming the largest of these areas as an indicator of the magnitude of the eruption, we will refer to those events whose deposits have covered areas not larger than 100 and 500, and larger than 500 km^2 as low-, medium-, or high-magnitude eruptions, respectively. The explosive eruptions were low- to medium-
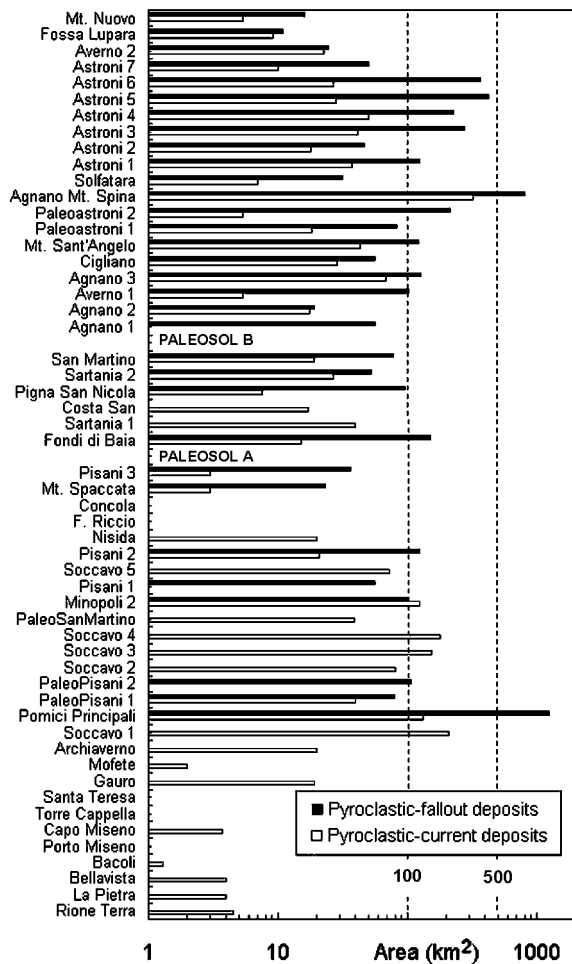
Fig. 3 Areas covered by pyroclastic-fallout and -current deposits of the Campi Flegrei caldera over the past 15 ka

Fig. 4a,b Sr/Sr isotope ratio (**a**) and CaO content (**b**) versus time of the Campi Flegrei volcanic rocks

magnitude events, except two high-magnitude events, one in the I and another in the III epoch.

During the I epoch, which lasted from 15 to 9.5 ka, not less than 37 explosive eruptions took place (Fig. 2). Among them only the Pomici Principali (10.3 ka; Lirer et al. 1987; Di Vito et al. 1999) was a high-magnitude eruption. The distribution of the vents in the I epoch (Fig. 1a) suggests that magmas reached the surface through all the marginal faults of the NYT caldera and only through some faults within the caldera floor.

After a quiescence of about 1 ka, the II epoch began and lasted from 8.6 to 8.2 ka, giving rise to 6 explosive, low-magnitude eruptions, occurring at an average interval of 65 years (Fig. 2). Vents were along parts of the marginal faults of the NYT caldera (Fig. 1a,e).

During a 3.5 ka long quiescence, between the II and III epochs, a change in the stress regime occurred in the caldera. Since the NYT caldera collapse, sea level has been rising (Aloisi et al. 1978), while the La Starza block has been uplifted at variable mean resurgence rate (Cinque et al. 1985; Orsi et al. 1996; Di Vito et al. 1999). The block has alternated periods of emersion and sub-
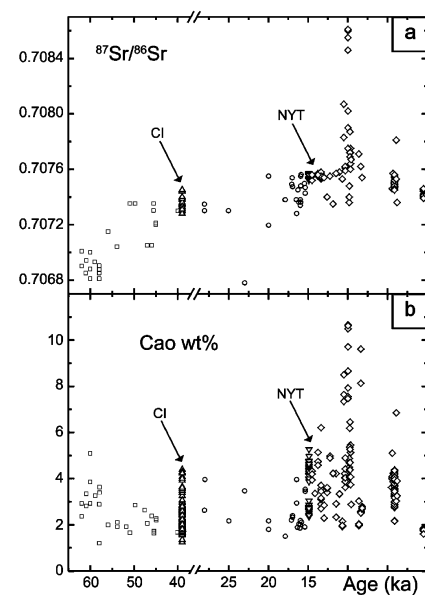
mersion until its ultimate emersion before onset of the III epoch (Fig. 2).

The III epoch lasted from 4.8 to 3.8 ka and produced 20 explosive and 3 effusive eruptions, which followed each other at mean intervals of 40 years. During this epoch, Agnano-Monte Spina (4.1 ka; de Vita et al. 1999; Dellino et al. 2001) was the only high-magnitude eruption and was accompanied by a volcano-tectonic collapse. Vents were along the faults intersecting the north-eastern portion of the NYT caldera floor, corresponding to the sector of the resurgent block under tensional stress regime (Fig. 1a,e, Orsi et al. 1996).

The last period of quiescence was interrupted in 1538 A.D. by the Monte Nuovo eruption (Figs. 2, 1a). This event, as the earlier two Averno eruptions, took place at the intersection of two fault systems delimiting the resurgent block (Fig. 1a,e).

Magmatic system

The results of recent petrological studies have shown that the magmatic system of the CFc is very complex (D'Antonio et al. 1999; Pappalardo et al. 1999, 2002b; Marianelli et al. 2003). A plausible interpretation of both structure and evolution of the system implies the existence of a shallow (about 4 km) trachytic reservoir, sometimes refilled at least over the past 60 ka (Fig. 4a, b), by new magma batches rising from a storage zone located between 10 and 15 km depth. Complex differentiation processes, mainly crystal fractionation and mingling/mixing, and subordinately contamination, have operated within the shallow portion of the magmatic system. From 60 to 44 ka, input of new magma batches produced the growth of this portion of the magmatic system. From 44
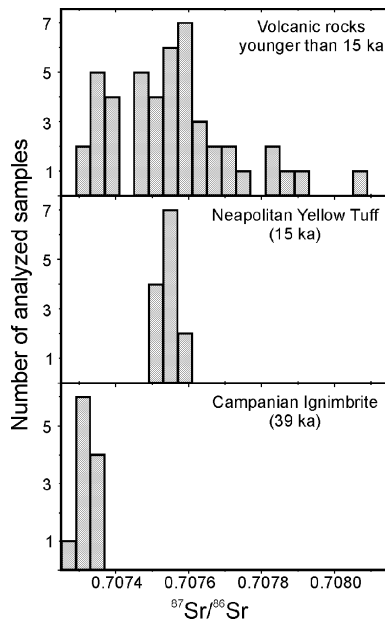
Fig. 5 Sr-isotope data of the Campi Flegrei caldera volcanic rocks younger than 15 ka compared with data of the Neapolitan Yellow Tuff and Campanian Ignimbrite (modified after D'Antonio et al. 1999)

to 39 ka, it was an isotopically homogeneous, large-volume, zoned reservoir, whose evolution culminated in the CI catastrophic eruption (not less than 200 km^3 DRE; Fedele et al. 2003). The isotopic variations shown by the rocks erupted between 39 and 15 ka indicate arrival of new magma batches, forming an apparently independent, large-volume reservoir which fed the NYT eruption (40 km^3 DRE; Orsi et al. 1992). In the past 15 ka, three isotopically and geochemically distinct magmatic components were erupted (Fig. 5) as either homogeneous or mixed magma batches (D'Antonio et al. 1999). One component is similar to the trachytic magma extruded during the CI eruption, the second is similar to the latitic-alka-litrachytic magma extruded during the NYT eruption, the third component is a trachybasalt never erupted before. D'Antonio et al. (1999) have hypothesised that the CI and NYT components represent residual portions of older, large-volume magma reservoirs. The least-evolved component was erupted only during the I and II epochs of activity, through vents located on a NE-SW regional fault system. This component likely represents the deeper seated magma tapped by regional faults.

Short-term deformation

The NYT caldera has been affected by ground deformation over the past 2 ka, documented at the Serapeo roman market in Pozzuoli (Fig. 1d$_1$) (Parascandola 1947; Dvorak and Gasparini 1991). Two major unrest episodes (bradyseismic events) have occurred between 1969 and 1972, and 1982 and 1984 (Fig. 1d$_2$) (Casertano et al. 1976; Corrado et al. 1977; Barberi et al. 1984, 1989; Berrino et

al. 1984; De Natale and Pingue 1993; Bonafede and Mazzanti 1998; Orsi et al. 1999a). The maximum ground uplift was about 170 cm during the first, and about 180 cm during the second episode. Since 1984 the ground has been generally affected by subsidence, which has been interrupted by small episodes of inflation in 1989 (7 cm), 1994 (<1 cm), and in 2000 (4 cm) (Osservatorio Vesuviano; internal reports). Only 85 cm of the net uplift has been recovered. During all episodes of uplift the maximum ground deformation has been measured in the area of Pozzuoli. This short-term deformation has been interpreted by Orsi et al. (1996, 1999a, b) as the result of the interplay of a ductile and a brittle component. The authors have suggested that both components are generated by pressure and temperature increase in the shallow magma reservoir due to arrival from depth of small magma batches, less evolved and hotter than the resident magma. The ductile component could result from expansion and migration of geothermal fluids due to temperature increase. The brittle component could be generated by slip along fault planes in the shallow crust above the magma reservoir. Ground deformation data and both epicentres and hypocentres location of the earthquakes occurred during the bradyseismic events, show that the deformed area has a polygonal shape defined by fault systems of the resurgent block inside the NYT caldera (Orsi et al. 1999a). This geometry is also well constrained by SAR interferometry data (Lundgren et al. 2001). The striking similarity between ground deformation geometry occurred during the recent bradyseismic events and that of the III epoch, suggests that the resurgence dynamics is not changed since the quiescence period between the II and III epoch. The similarity in shape between long- and short-term deformation corroborates the hypothesis that the former results from the summation of many short-term deformation events (Orsi et al. 1996).

Present state

The reconstruction of the thermal history of the Campi Flegrei magmatic system (Wohletz et al. 1999) has permitted to estimate the present setting of the thermo-fluid dynamical system and to hypothesise its contribution to the evolution of the recent bradyseismic events (Orsi et al. 1999b). The present state of the system results from a sequence of input of new magma batches from depth and extrusion through eruptions since at least 60 ka. Based on stable isotope data, the fumarolic fluids are interpreted as magmatic fluids variably contaminated by meteoric components (Allard et al. 1991) and buffered by a large hydrothermal system. This system dissipates the heat through boiling and feeds a superheated upper re-equilibrated vapour zone. Gas equilibria in the CO_2-CO-CH_4-H_2O-He system indicate that temperature and P_{H2O} conditions in the superheated vapour zone has varied from 240 °C and 30 bar, during the 1982–1984 unrest episode, to 210–220 °C and 3–7 bar, at present (Chiodini and Marini 1998). The geothermal gradients measured in deep

wells (Agip 1987) are very high. Their variation with depth suggests that heath is transferred by conduction and convection. The latter is separated from the magmatic system and likely confined in the caldera fill. Analyses of fluid-solid interaction (Orsi et al. 1999b), based on the present state of the system (D'Antonio et al. 1999; Wohletz et al. 1999; Di Maio et al. 2000; Iuliano et al. 2000), have also shown that lateral migration of fluids can be a component of the ductile deformation of the shallow crust during subsidence. The results of these analyses explain the absence of seismicity during subsidence and corroborate the hypothesis that the bradyseismic events are transient episodes in the long-term evolution of the thermal system (Orsi et al. 1996; 1999a).

Impact of the Phlegraean volcanism on the Neapolitan area over the past 15 ka

Effusive eruptions

Although deposits of effusive eruptions (Monte Spina, Monte Olibano and Accademia) have been found only in the stratigraphic sequence of the III epoch (Di Vito et al. 1999) (Figs. 2, and 1a), we cannot exclude that similar eruptions have taken place also during the previous epochs. The exposed products are remnants of small-volume trachytic to trachybasaltic lava domes and lava flows. The latter flowed only a few hundred meters over gentle slopes and formed massive bodies with steep fronts.

Explosive eruptions

Almost all explosive eruptions have alternated magmatic to phreatomagmatic explosions and have generated tephra fallout and pyroclastic currents. Furthermore the occurrence of contemporaneous magmatic and phreatomagmatic fragmentation dynamics has also been recognised (de Vita et al. 1999; Dellino et al. 2001, 2004a). Almost all the pyroclastic currents were expanded and turbulent flows produced by phreatomagmatic explosions (Di Vito et al. 1999; Dellino et al. 2001, 2004b). Many eruptions produced high proportions of ash, which was transported either in the umbrella portion of the eruption columns or as continuous suspension in the slow-moving upper part of the pyroclastic currents, not affected by significant shear (Walker 1984; Dellino and La Volpe 2000; Dellino et al. 2004b). This implies that distal structureless fine-ash beds cannot be easily correlated to proximal fallout or pyroclastic-current deposits, unless their stratigraphic position is constrained by marker beds.

Areal distribution and thickness variation of pyroclastic deposits

Areal distribution and thickness variation maps for pyroclastic-current and -fall deposits, respectively, have

been constructed in order to have a basic tool to perform a volcanic hazards zoning of the area. The areal distribution maps for pyroclastic-current deposits have been constructed considering the areas in which the deposits still show structures that indicate a horizontal component in the transport of the particles. This criterion and scattering of outcrops, natural erosion and urbanisation, results in a conservative estimation of the areas affected by the currents. However, available run-out models (i.e. Malin and Sheridan 1982) cannot be applied as they have been developed for currents generated by column collapse. Isopach maps for fallout deposits have been constructed for a minimum thickness of 10 cm; thinner beds usually are not precisely measurable in the field. In these maps we have also included the structureless ash beds that could have been deposited by the upper part of the pyroclastic currents because the effects on the territory, lacking the horizontal component of the transport, can be assumed as similar to that of falling tephra.

The pyroclastic deposits of the I epoch (15–9.5 ka) were distributed over a wide area. We have constructed isopach maps for 8 fallout deposits and areal distribution maps for 24 pyroclastic-current deposits (Fig. 6a, b). The reconstructed limit of maximum sea ingression in the time interval 8.2–4.6 ka (Di Vito et al. 1999) has been assumed as the boundary between continental and marine deposition of pyroclastic rocks within the NYT caldera floor.

Fallout deposits were laid down over the north-eastern sector of the CFc floor and the northern slopes of the Camaldoli hill, up to the Campanian plain (Fig. 6a). The 10-cm isopach of the fallout beds of the Pomici Principali Tephra encompasses an area of about 1,250 km^2 and extends towards the east, as far as the Apennines. The area covered only once with fallout deposits 10 cm or more (Fig. 6c) was dominantly affected by this tephra. The smaller area covered two or three times is sub-circular and comprised among the city of Naples to the south-east, and the towns of Pozzuoli and Qualiano to the south-west and north, respectively. The north-western part of the city of Naples and the towns of Quarto and Marano were covered between four and six times. Only a small area north-west of the Camaldoli hill was affected by fallout deposition seven or eight times.

Pyroclastic currents deposited their load over the NYT caldera floor, including the sector presently occupied by the western part of the city of Naples, the northern slopes of the Camaldoli hill, and a portion of the plain north of Cuma (Fig. 6b). Most of the pyroclastic-current deposits (7–10) were laid down in the northern and eastern sectors of the CFc depression and over the northern slopes of the Camaldoli hill (Fig. 6d). Flowage of the currents towards the city of Naples and over the northern slopes of the Camaldoli hill was favoured by both location of sub-aerial vents (Fig. 7a), and morphological characteristics of the southern and western scarps of the Camaldoli hill (Fig. 6b). These scarps were intersected by deep valleys, and their slope varied between 12° and 70°. Both deep valleys (i.e. Verdolino and Via Pigna) and low-angle portions of the scarps (i.e. Torciolano) were preferential ways for the
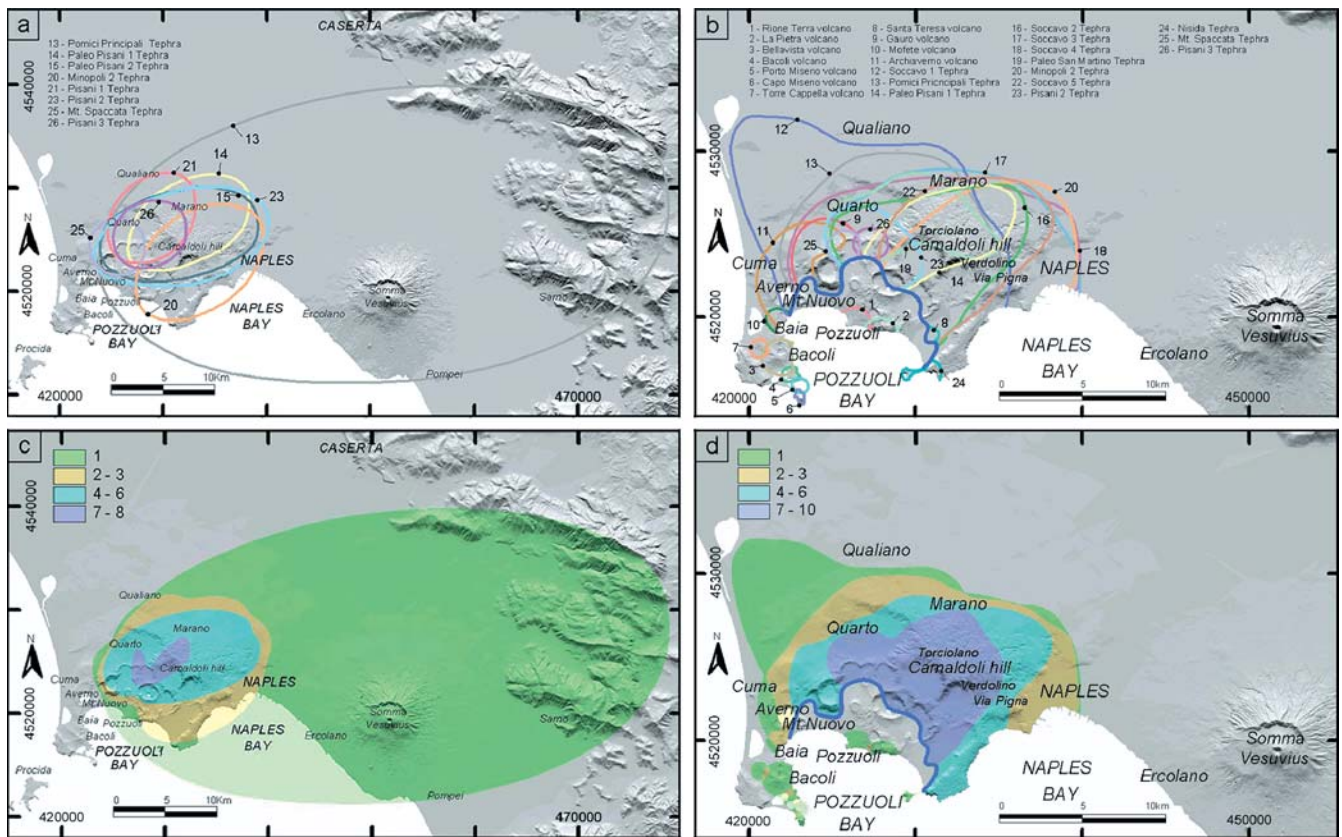
Fig. 6a–d Distribution of the pyroclastic deposits of the I epoch. (**a**) 10 cm isopachs of the fallout deposits; (**b**) areal distribution of the pyroclastic-current deposits; (**c**) frequency of deposition of fallout beds thicker than 10 cm; (**d**) frequency of deposition of pyroclastic-current beds. *Thick blue line* in b and d is the limit of the maximum sea ingression between 8.2 and 4.6 ka B.P.

pyroclastic currents to exit the lowland of the caldera floor.

The pyroclastic deposits of the II epoch (8.6–8.2 ka) were more restricted in distribution than those of the I epoch. We have constructed isopach maps for the fallout deposits of four eruptions and areal distribution maps for the pyroclastic-current deposits of six eruptions (Fig. 7a,b). Fallout deposits of 10 cm or more covered only once portions of the city of Naples and of the towns of Bacoli, Pozzuoli, Quarto, Qualiano and Marano. An area extending from the north-eastern portion of the CFc, including parts of the city of Naples and of the towns of Quarto and Pozzuoli, to the plain north of Cuma, was covered two or three times (Fig. 7c). The pyroclastic-current deposits of this epoch were deposited within the caldera floor and over the northern and eastern slopes of the Camaldoli hill (Fig. 7b). Currents flowed mostly within the north-eastern sector of the CFc (Fig. 7d). As during the I epoch, some of the currents, in favourable morphological conditions, were able to surmount the southern and western scarps of the Camaldoli hill.

The pyroclastic deposits of the III epoch (4.8–3.8 ka) and those of the Monte Nuovo eruption (1538 A.D.) were dispersed over a similar area to the I epoch. We have constructed isopach maps for the fallout deposits of 20 eruptions (Fig. 8a) and areal distribution maps for the

pyroclastic-current deposits of 19 eruptions (Fig. 8b), including the Monte Nuovo Tephra. Fallout deposits not thinner than 10 cm, were deposited only once over an area defined almost exclusively by the fallout beds of the Agnano-Monte Spina Tephra (Fig. 8c), and not less than two or three times over the area extending from the city of Naples to the towns of Qualiano and Bacoli, towards the north and the west, respectively. Pyroclastic currents were mostly confined within the caldera floor and subordinately over the northern slopes of the Camaldoli hill (Fig. 8d). Only the currents of the Agnano-Monte Spina and Astroni eruptions travelled minimum distances of about 20 and 10 km, respectively. The areas more frequently invaded by pyroclastic currents were the central and eastern sectors of the caldera floor, which include portions of the city of Naples and of the towns of Pozzuoli and Quarto.

The maximum cumulative thickness of the fallout beds laid down over the past 15 ka is about 15 m (Fig. 9), resulting from 6, 2.5 and 7.5 m deposited in the I, II and III epoch, respectively. The highest values (>400 cm) occur in the north-eastern sector of the caldera floor, in the western part of the city of Naples and along the northern slopes of the Camaldoli hill. This area, about 90 km^2 in size, includes parts of the city of Naples and of the towns of Pozzuoli, Quarto and Marano.
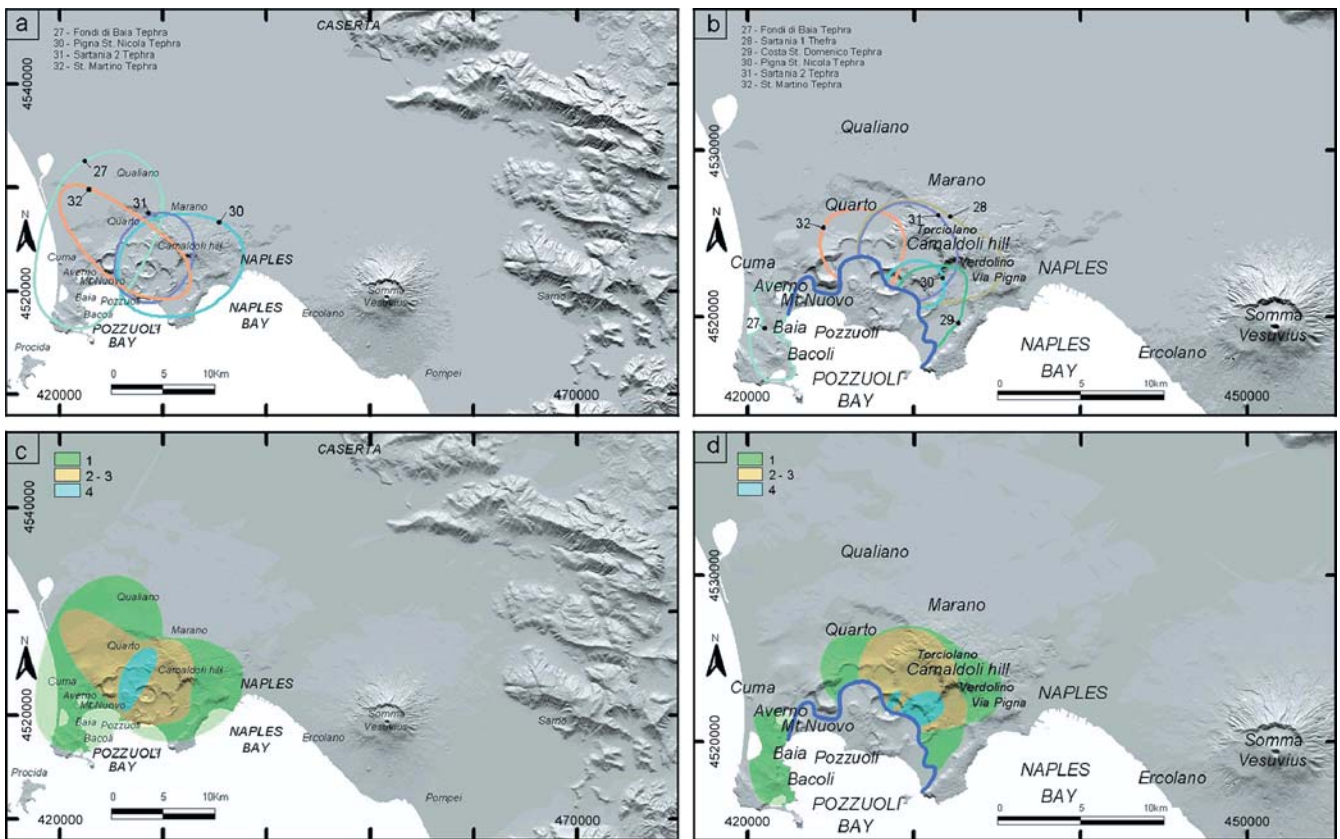
Fig. 7a–d Distribution of the pyroclastic deposits of the II epoch. (**a**) 10 cm isopachs of the fallout deposits; (**b**) areal distribution of the pyroclastic-current deposits; (**c**) frequency of deposition of fallout beds thicker than 10 cm; (**d**) frequency of deposition of pyroclastic-current beds. *Thick blue line* in b and d is the limit of the maximum sea ingression between 8.2 and 4.6 ka B.P.

Load exerted on the ground by fallout deposits

Using thickness and density of the single layers of the fallout deposits of the last 5 ka, we have calculated the load exerted on the ground from the deposits of each eruption. About 50 density measurements have been carried out on a known volume of fallout deposits with variable sedimentological characteristics, at the Laboratory of the Department of Geotechnical Engineering of the University of Naples Federico II. The mean values for deposits with a lithic content lower than 30% and including either well vesiculated lapilli-sized pumice fragments or less vesiculated, more dense, lapilli-sized scoriaceous fragments, are 600 and 1,000 kg/m^3, respectively. For ash layers we have used a density of 1,650 kg/m^3, which is the value at water-saturated conditions. These values are relatively high because of both the high crystallinity of juvenile fragments and the occurrence of lithic clasts with density in excess of 2,000 kg/m^3. Using these density values and the stratigraphic sequences of the pyroclastic units of the III Epoch we have assigned density values of 900 kg/m^3 to the Agnano-Monte Spina and Averno 2 Tephras, 1,000 kg/m^3 to the Fossa Lupara, Monte Nuovo, Astroni 7 and Paleoastroni 2 Tephras, and 1,650 kg/m^3 to the Agnano 1, Agnano 2, Agnano 3, Averno 1, Cigliano, Monte Sant'Angelo, Paleoastroni 1, Solfatara and Astroni 1–6 Tephras.

The literature on building damage by tephra accumulation is very scarce. Blong (2003) has published data on the damage caused to residential buildings in Rabaul by accumulation of tephra of the 1994 eruption. According to the Volcanic Damage Index that the author developed by modifying the index previously proposed by Spence et al. (1996), residential buildings with steel roofs on timber frame, began to suffer "heavy damage" (index V3) for a tephra load of 2.0 kN/m^2. Lower load values were defined by Pomonis et al. (1999) for damage to buildings with very poorly constructed roofs, by tephra accumulation in relation to a future eruption of Furnas volcano (Azores). Spence et al. (1996) investigated building damage caused by 20 cm of tephra accumulated after the 1991 Pinatubo eruption. The authors hypothesised that a design load of 2.0 kN/m^2 would have likely been sufficient to avoid collapse of roofs, generally covered with corrugated galvanized steel sheets. According to the most frequent typologies of the residential buildings of the Neapolitan area, Pareschi et al. (2000) have assumed that 7, 19, 42, and 67% of the roofs would collapse under a load of 2.0, 3.0, 4.0 and 5.0 kN/m^2, respectively. These load values have been used by the Italian Department for Civil Defence in developing the Vesuvius Emergency Plan.
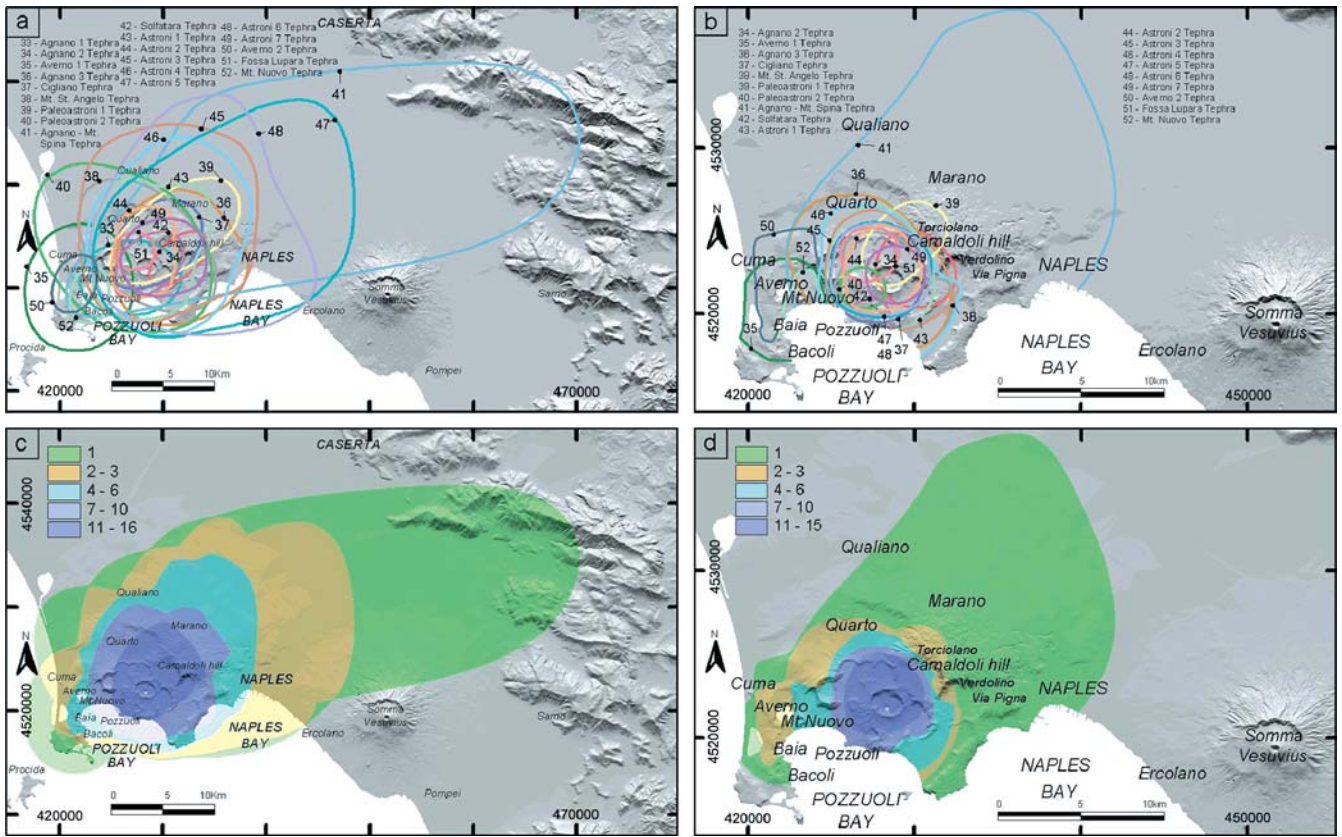
Fig. 8a–d Distribution of the pyroclastic deposits of the III epoch and of Monte Nuovo. (**a**) 10 cm isopachs of the fallout deposits; (**b**) distribution of the pyroclastic-current deposits; (**c**) frequency of deposition of fallout beds thicker than 10 cm; (**d**) frequency of deposition of pyroclastic-current beds
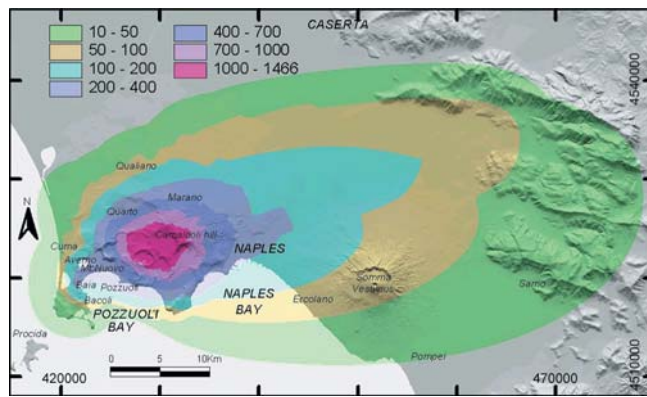

Fig. 9 Cumulative thickness of the fallout deposits (in cm) of the last 15 ka

Therefore, in order to evaluate the impact of tephra accumulation on the Neapolitan territory by the fallout deposits of the III epoch of activity of the CFc, we have constructed frequency maps for load in excess of 2.0, 3.0, 4.0, and 5.0 kN/m^2 (Fig. 10a, b, c, d). The area which was more frequently affected by heavy tephra load corresponds to the area more frequently invaded by pyroclastic currents and includes the CF lowland and its north-eastern surroundings.

Volcanic hazard assessment and zoning

The basic questions of a volcanic hazard assessment and a zoning of the exposed territory are "when", "where" and "how" the next eruption will occur. The geological, volcanological, petrological, and geochronological data available for the CFc, allow these questions to be addressed in case of renewal of volcanism in short-mid terms. The NYT eruption and related caldera collapse has been the last major event which has significantly modified the conditions of the CFc system (Orsi et al. 1996). Furthermore, the relationships between the dynamics of the caldera and structural location of the active vents through time, show that during the second period of quiescence (8.2–4.8 ka), prior to the beginning of the III epoch, the stress regime within the NYT caldera changed (Di Vito et al. 1999). This regime still persists as shown by the dynamics of the recent bradyseismic events (Orsi et al. 1996, 1999a, b). Therefore, in the hazard assessment, we have taken into particular consideration the system's behaviour over the past 5 ka and its present state.
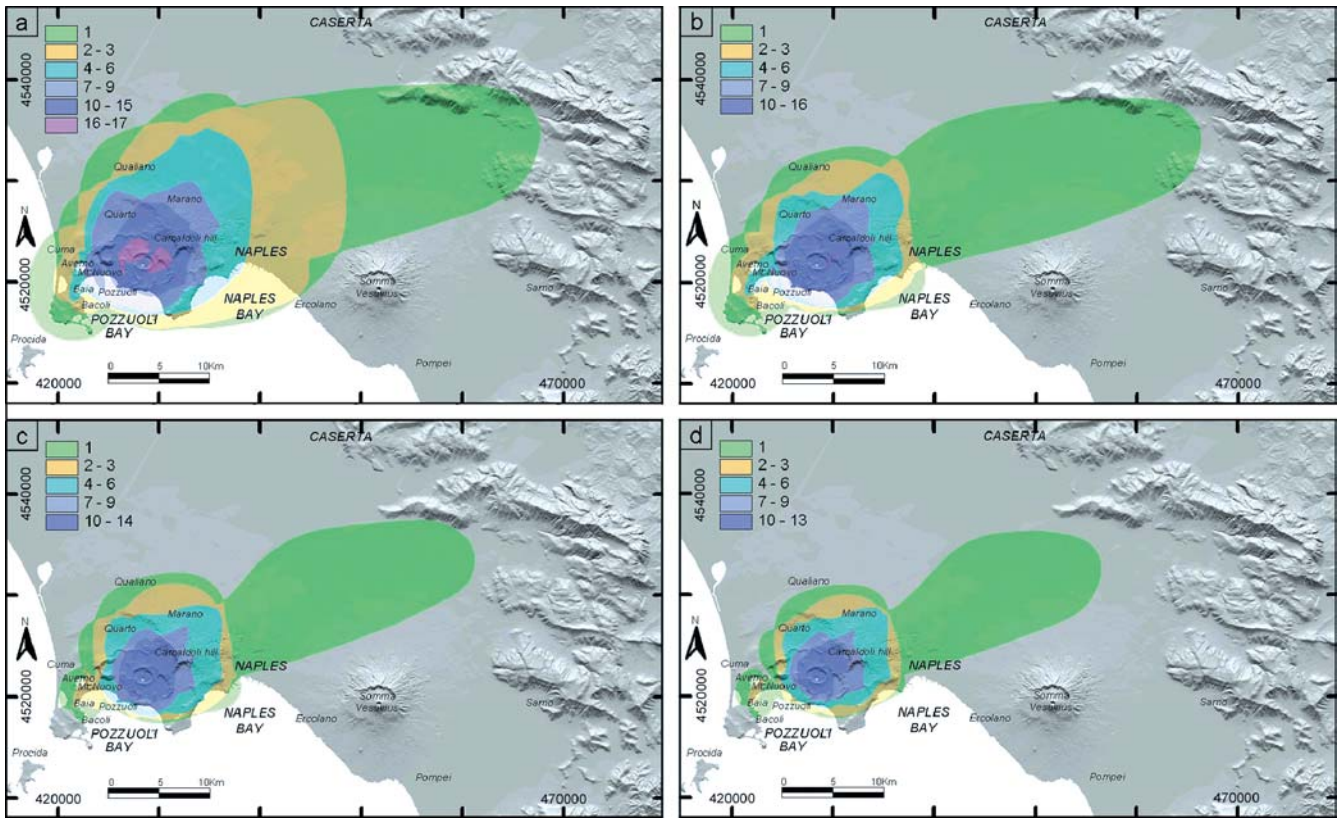
Fig. 10a–d Frequency maps of the fallout deposits with load on the ground in excess of 2.0 kN/m^2 (**a**), 3.0 kN/m^2 (**b**), 4.0 kN/m^2 (**c**) and 5.0 kN/m^2 (**d**)

When

Although it is not possible to state when an eruption will occur, we take the strait relationships between vents distribution of the III epoch and dynamics of the ongoing deformation of the NYT caldera (Orsi et al. 1996, 1999a) as an empirical evidence to hypothesise that the next eruption could likely occur when the structural conditions will allow ascent of magma to surface. Meantime we cannot rule out the possibility that an eruption could be triggered by build up of overpressure unrelated to tectonic processes and may impose a stress regime or even change the stress regime. The mechanism of resurgence (Fig. 1c), including the recent unrest episodes, generates compression within the south-western portion of the NYT caldera, corresponding to the bay of Pozzuoli, and extension within the north-eastern portion, including the area between the Agnano and San Vito plains. The latter has been the site of the largest majority (21) of the eruptions in the III epoch of activity (Fig. 1a). If extension results in normal faults, the conditions for magma to ascent to surface would be facilitated and volcanism could begin. Conditions for magma to rise to surface can also be acquired along reverse faults at their intersection with other marginal faults of the resurgent block, contemporaneously activated, as was the case for the Averno and Monte Nuovo eruptions.

Where

The answer to this question is closely connected to the answer to the question "when" the next eruption will occur. If the next eruption will be triggered by the ongoing dynamics of the NYT caldera, the most likely area within which a new vent could open is the north-eastern sector of the NYT caldera floor (Fig. 11). This area corresponds to the portion of the resurgent block under extension and has been the site of 18 out the 20 explosive eruptions of the III epoch. This area extends over about 12 km^2 between the San Vito and Agnano plains, and includes the western periphery of the city of Naples and part of the town of Pozzuoli.

The vents of the Monte Nuovo eruption and of the two events of Averno (III epoch), are located at the intersection of the faults within the portion of the resurgent block subject to compression and faults bordering the block towards the north-west. We cannot exclude that a future vent could open in these structural conditions and, therefore, in the same area (Fig. 11) which is about 3 km^2 wide and includes parts of the towns of Pozzuoli and Bacoli.
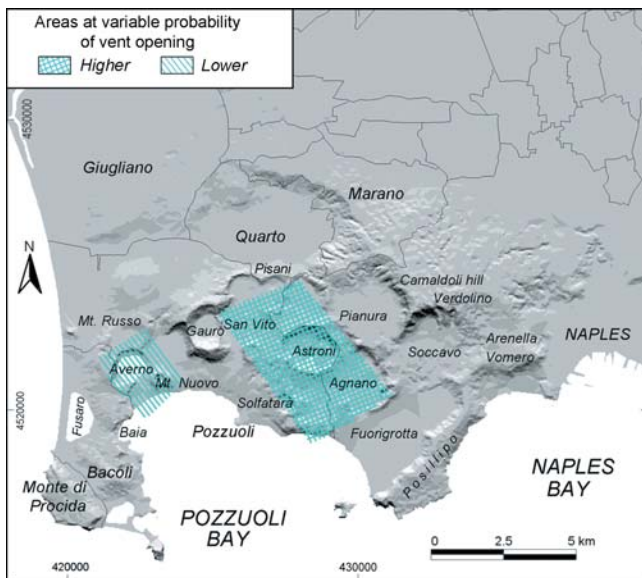
Fig. 11 Areas at variable probability of vent opening in case of renewal of volcanism in short-mid terms at the Campi Flegrei caldera

How

Precursors

A future eruption at the CFc likely will be preceded by precursors. According to the reconstructed resurgence dynamics and the relationships between short- and long-term deformation, the unrest episodes that occurred over the past 30 years could be its long-term precursors.

The Monte Nuovo eruption, the only historical event of the caldera occurred in 1538 A.D., was preceded by tens of years of ground uplift (Parascandola 1947). Since the beginning of the XVI century, there was an acceleration of the uplift as testified by royal edicts (Orsi et al. 1999a and references therein). Uplift of the La Starza block may be accompanied by fracturing and faulting of the crust in the Agnano-San Vito area, and intense seismicity. Ground deformation and seismicity could trigger landslides. Fracturing should also produce an increase in fluids circulation with related increase in fumarole activity. Evolution of fractures to faults could decompress the magma with consequent increase in gas exsolution. The exsolved gases will rise to surface and therefore the amount of emitted fluids will increase and their composition will change. Due to increased circulation of deep and hot fluids, the shallow water table of the Agnano-San Vito area (Celico et al. 1992; Corrado et al. 1998), could be overheated and generate phreatic explosions.

The eruption

Although there is evidence of only 3 effusive events over the past 15 ka, we cannot exclude that the next eruption could be effusive. Such an eruption would be fed by
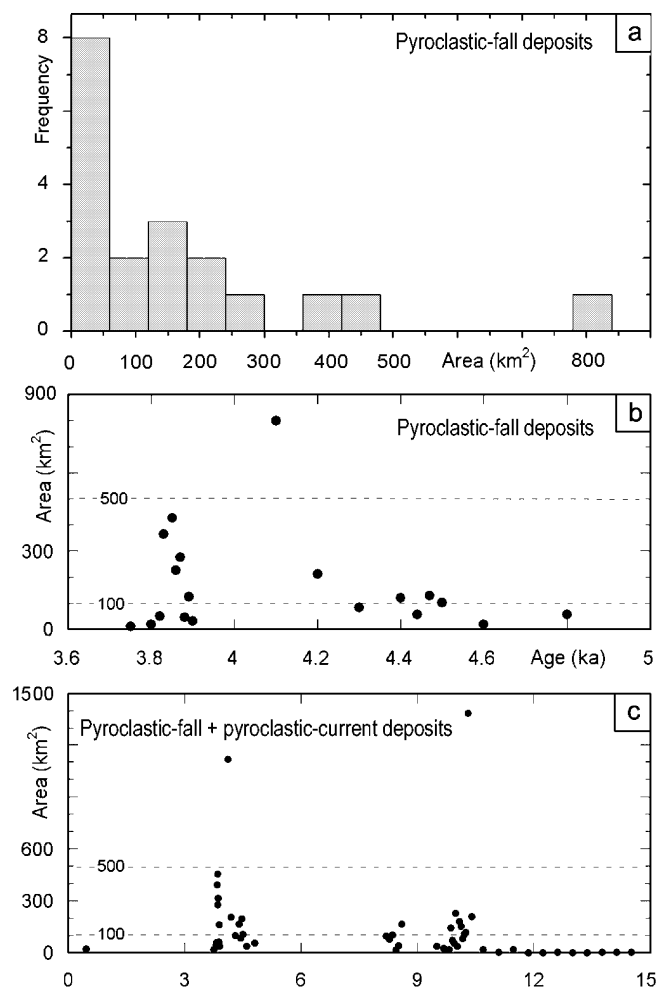

Fig. 12a–c Frequency diagram of the area covered by the pyroclastic-fall deposits of the III epoch (**a**); area covered by the pyroclastic-fall deposits of the Campi Flegrei caldera eruptions in the past 5 ka, versus time (**b**); area covered by the pyroclastic-fall and pyroclastic-current deposits of the Campi Flegrei caldera eruptions in the past 15 ka (**c**)

trachytic viscous magma, which would generate a lava dome and/or a high aspect-ratio lava flow.

In order to hypothesise the magnitude of the next eruption we have taken into account the past behaviour of the caldera (Fig. 3). A frequency diagram shows a polymodal distribution of the magnitude of the eruptions of the III epoch (Fig. 12a). The 10 cm or more fallout deposits of 8 eruptions (42%) covered an area smaller than 60 km^2, those of 8 more events were dispersed over an area ranging from 60 to 500 km^2 in size, with a mode at 150 km^2, and only those of the Agnano-Monte Spina eruption were laid down over about 800 km^2. Excluding the fallout deposits of Agnano-Monte Spina, two modes can be recognised. Taking into consideration the uncertainty in measuring dispersal areas, we assume 0 and 100 km^2, and 100 and 500 km^2 as limit values for the two modes. The variation of the explosive eruptions magnitude during the course of the III epoch followed a well-
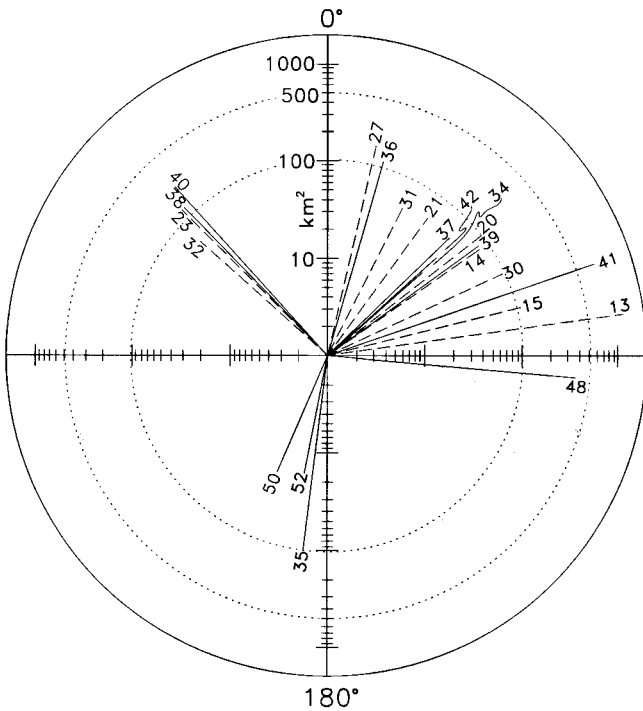
Fig. 13 Dispersal axes for the 10-cm-thick fallout deposits of the past 15 ka. *Solid lines* refer to deposits of the III epoch. Units are identified by numbers as in Figs. 6, 7 and 8

defined trend (Fig. 12b); it increased till the plinian Agnano-Monte Spina eruption and then decreased. The eruption's magnitude had a similar time variation also during the I epoch (Fig. 12c). During the II epoch, the magnitude (low to medium) of all the six explosive eruptions did not show any systematic trend with time (Fig. 12c). As for a number of eruption sequences of the I and II epochs pyroclastic-fallout deposits have not been recognised, we have used as an indicator of the magnitude the sum of the areas covered by pyroclastic-current and -fallout deposits. Isaia et al (2003) have demonstrated that the magnitude of the seven eruptions of the Astroni volcano, which grew within the volcano-tectonic collapse related to the Agnano-Monte Spina eruption, also increased and then decreased through time. The authors have also shown that the eruptions which produced fallout deposits covering areas in the 100–500 km^2 size range, extruded volumes of magma varying between 0.04 and 0.13 km^3 (DRE). The behaviour of the system in the past 5 ka, and more in general in the past 15 ka, suggests us to consider as the most probable maximum event in the case of renewal of volcanism in short-mid terms, an eruption similar to the medium-magnitude events of the past 5 ka, although an eruption of Agnano-Monte Spina size could be assumed as the maximum expected event. Furthermore, considering the volumes of magma erupted during the Astroni volcano activity and the available petrological data, we suggest that the most probable maximum expected eruption could be fed by a volume of trachytic magma varying in the same range of that extruded during the Astroni activity.

Fig. 14 Tephra fallout hazard map of the Campi Flegrei caldera
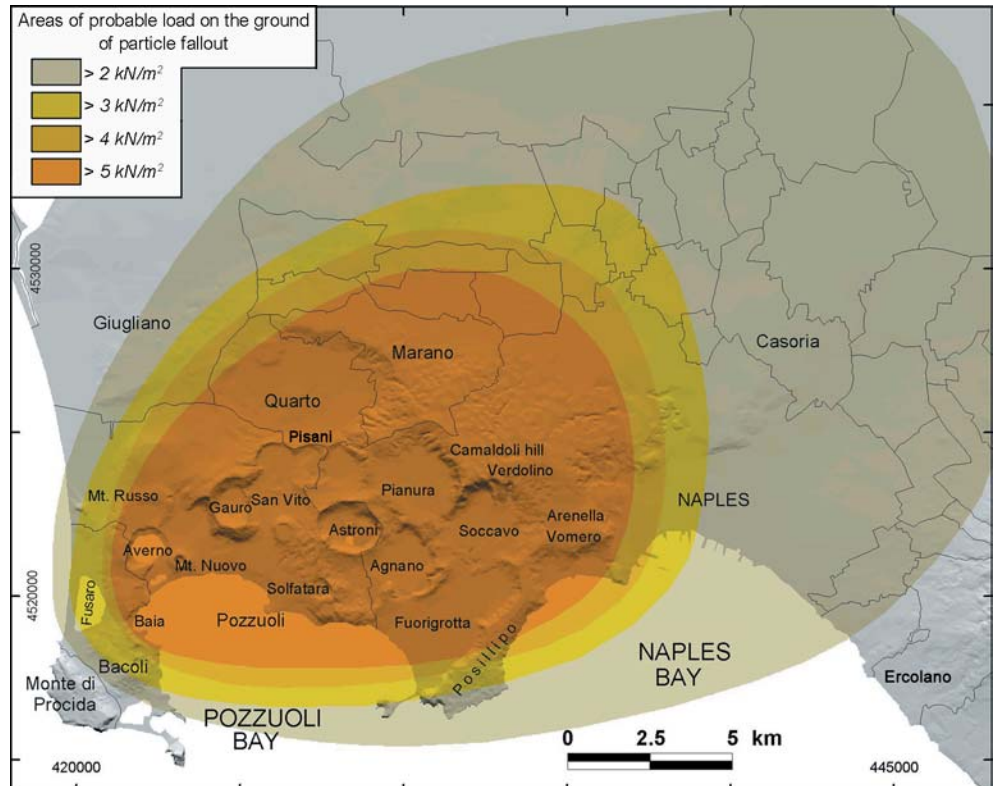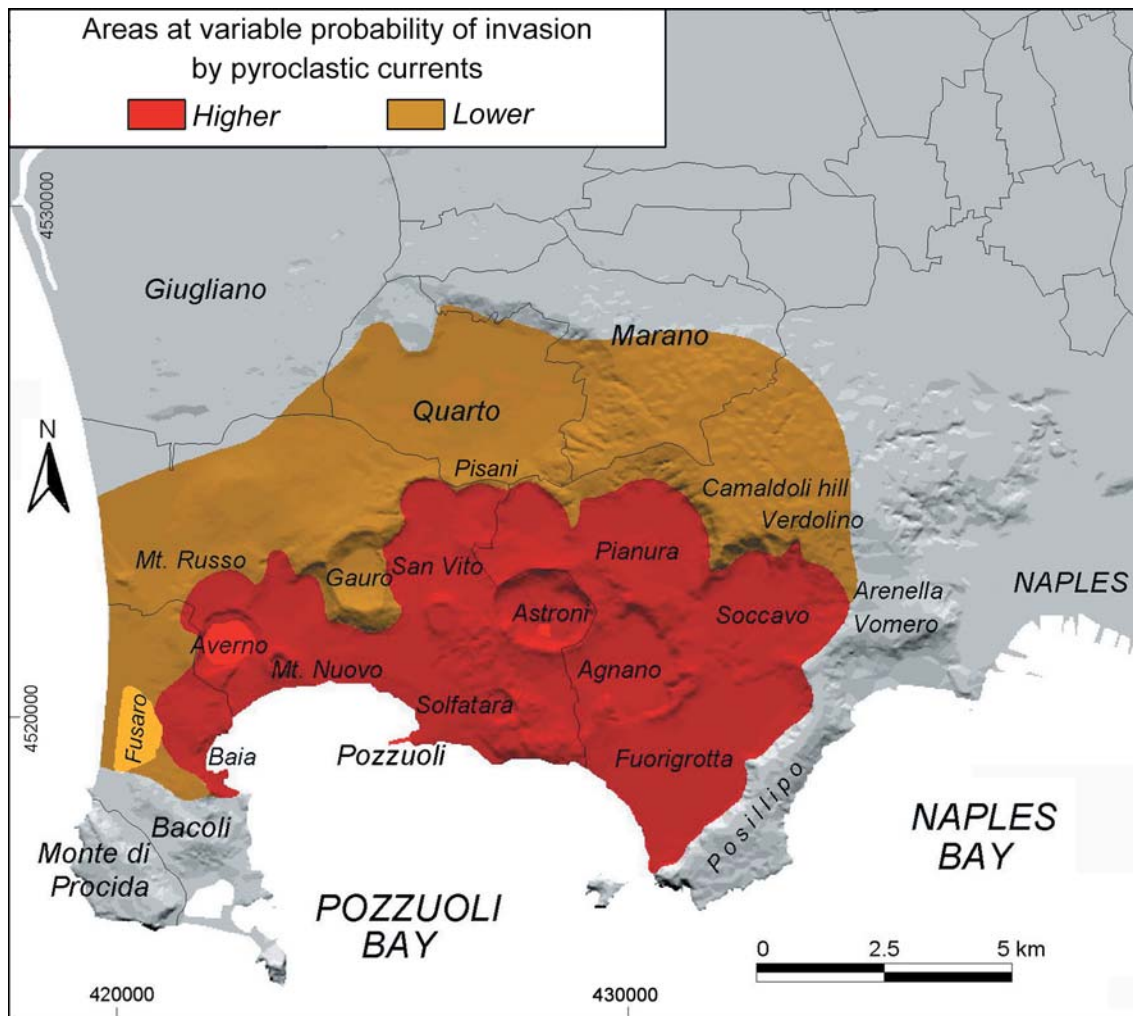
Fig. 15 Pyroclastic currents hazard map of the Campi Flegrei caldera

According to the reconstructed dynamics of the explosive eruptions of the last 5 ka, we hypothesise that the future explosive eruption will be characterised by alternation of magmatic and phreatomagmatic explosions. In such an eruption scenario, the hazards are tephra fallout and flowage of pyroclastic currents.

Tephra fallout will be likely generated by both magmatic and phreatomagmatic explosions. Dispersal axes directions of the fallout deposits of the low- and medium-magnitude eruptions of the past 5 ka do not differ from those of the past 15 ka (Fig. 13). The plumes from which these beds were deposited were driven by the wind towards almost any direction, although prevailingly towards the northeast. The largest majority of plinian and sub-plinian fallout deposits of the CFc, as well as those of the adjacent Vesuvius (Cioni et al. 2003; Orsi et al. 2003) are dispersed towards the east, indicating that at tens of kilometres height, winds have statistically dominant direction. Taking into consideration the frequency of deposition of fallout beds thicker than 10 cm (Fig. 8), frequency of load on the ground by tephra fallout (Fig. 10), direction of dispersal axes (Fig. 13) and the limit load of

collapse for the variable roof typologies, we have constructed a fallout hazard map (Fig. 14). In this map we have delimited the areas that could be affected by loads on the ground in excess of 2.0, 3.0, 4.0 and 5.0 kN/m^2. The portion of these areas which will be actually affected by fallout during the eruption, cannot be defined as it will depend on the wind direction at the height that the plume will reach.

Pyroclastic currents will be likely produced by phreatomagmatic explosions. On the basis of the areal distribution and frequency of the pyroclastic-current deposits during the past 5 ka (Fig. 8b, d), which show a significant similarity with those of the I and II epochs (Figs. 6b, d and 7b, d), and of the location of the areas in which a future vent could likely open (Fig. 11), we have constructed an hazard map for pyroclastic currents (Fig. 15). The western portion of the outer boundary of the area at lower probability of invasion by pyroclastic currents has been defined on the basis of the areal distribution of one single pyroclastic-current deposit (Averno 2), as this is the product of the only eruption which has generated energetic currents within the area at lower probability of
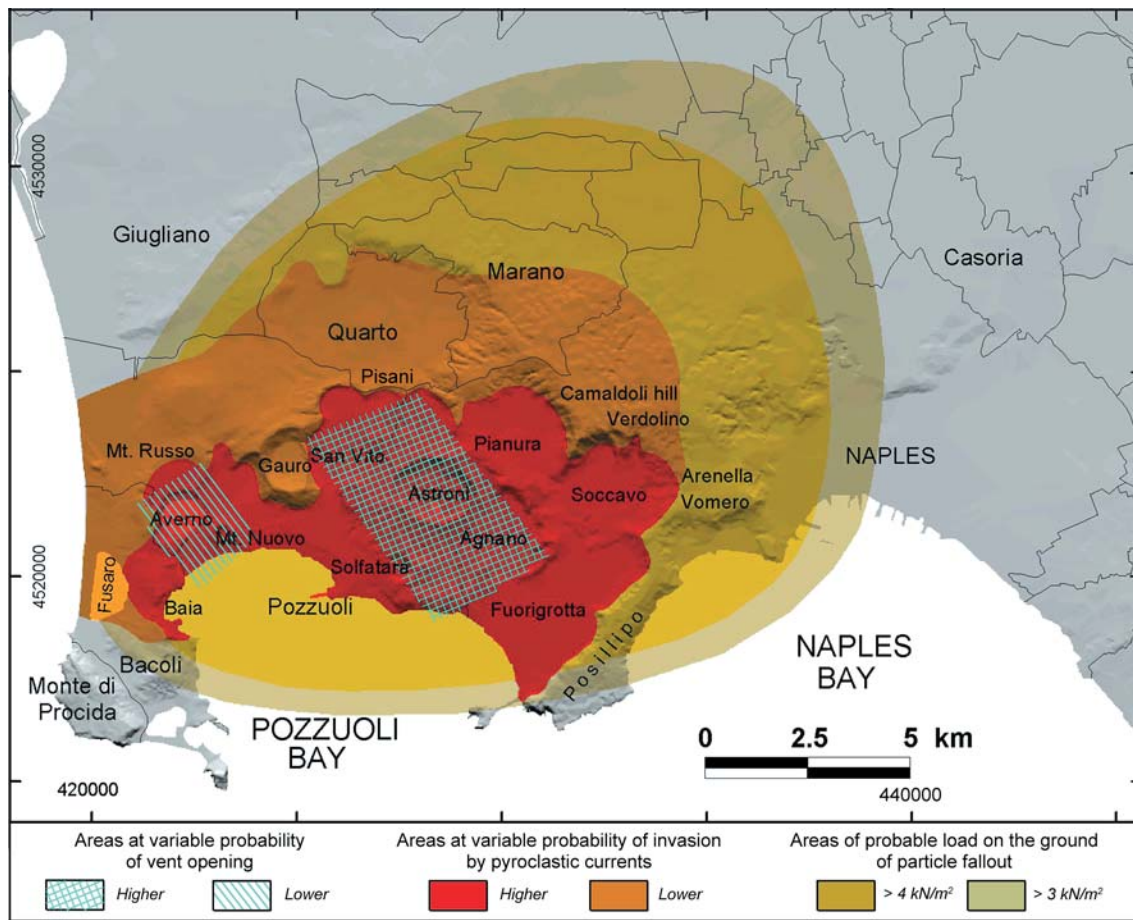
Fig. 16 Volcanic hazard map of the Campi Flegrei caldera

opening of a new vent. The currents likely will travel at high speed within portions of the Campi Flegrei lowland delimited by the Posillipo, Vomero, Camaldoli, Pisani, Gauro, Monte Russo and Baia alignment of morphological heights. This area includes parts of the city of Naples and of the towns of Pozzuoli and Bacoli. Some flows, depending upon vent location and energy, likely will be able to exit this lowland in favourable morphological conditions. Such conditions occur along the western slopes of the Vomero hill and the low-angle portion of the scarp bordering westwards the Camaldoli hill, at the Verdolino valley, and among the lowest portions of the northern boundaries of the lowland. They could allow the pyroclastic currents to reach the Camaldoli hill and the Vomero-Arenella sector of the city of Naples, the towns of Marano and Quarto, and the northern portions of the towns of Pozzuoli and Bacoli. Along the northern slopes of the Camaldoli hill, after transformation in overriding the morphological barrier, their flowage and areal distribution could likely be influenced by the morphology, which is characterised by a complex drainage system.

Phenomena related to the eruption

During each epoch, eruptions have followed each other at short time intervals. In particular, during the III epoch, prior to the plinian Agnano-Monte Spina event, volcanism has generated one eruption every 30 years, on average. Therefore, we cannot exclude that if volcanism will resume in the Agnano-San Vito area, it could generate eruptions at short time intervals. On the contrary, if volcanism will resume in the Monte Nuovo-Averno area the eruption could be a discrete event. A related phenomenon, which likely could occur during and/or after the eruption, despite the vent position, is the generation of mud flows. Ash covering the slopes of the caldera could likely be remobilised by heavy rains and flow mostly along the northern slopes of the Camaldoli hill and within the urban area of the city of Naples. Similar currents could also be generated along the slopes of the reliefs far from the caldera, such as those of the Somma-Vesuvius and the Apennines.

Conclusions

The reconstructed past behaviour and present state of the CFc system have allowed us to hypothesise the most probable maximum eruption in case of renewal of volcanism in short-mid terms, to perform a volcanic hazard assessment and to construct a comprehensive hazard map (Fig. 16). To accomplish these goals we have taken into particular consideration the behaviour of the system since 5 ka B.P., when its present stress regime was established.

A future vent most likely will open in the area between the Agnano and San Vito plains, which has been the site of the large majority of the eruptions of the past 5 ka and corresponds to the portion of the resurgent block under tensile stress regime. Another possible location of the vent could be in the Monte Nuovo-Averno area, at the junction of two fault systems.

An effusive eruption, which could generate a lava dome and/or a high aspect-ratio lava flow, cannot be ruled out. The past history of the caldera and in particular variation through time of the magnitude of explosive eruptions suggest that, although the Agnano-Monte Spina event, the largest of the past 5 ka, could be considered the maximum expected eruption, the most probable maximum eruption is a medium-magnitude eruption. The volcanic hazards which can be expected from such an eruption are tephra fallout and flowage of pyroclastic currents. Tephra fallout could affect a portion of the caldera and its surroundings, according to wind direction at the height reached by the plume. Pyroclastic currents, likely dilute and turbulent flows, would invade portions of the caldera lowland, depending upon vent location and energy. Very energetic currents could surmount morphological barriers and in favourable conditions, exit the lowland towards the north. Flowage of some of these currents could be influenced by the complex drainage pattern. Heavy rains could generate mud flows within the caldera and over large portions of its surroundings during and/or after the eruption.

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