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The Phlegrean Fields volcanological evolution

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ABSTRACT
A volcanological map merging continental and marine areas of the Phlegrean Fields and Procida Island (Southern Italy) is presented at the 1:25,000 scale. The map is based on 1:5,000 field mapping, and marine geology survey carried out during the Italian CAR.G (Geological CARtography, Servizio Geologico d'Italia) project and on bathymetric and seismic data. Geological data are represented on a digital terrain model of the volcano. This allows better visualization of the main morphological, volcanic, and geological features. The legend is organized in seven activity phases identified based on updated absolute ages of eruptions defining periods of high volcanicity and stasis. The geological map highlights the evolutive history of the Phlegrean Fields volcanic field both in the marine and continental portions, and the reconstructed structural framework and evolution of the caldera formed 39.3 Ky ago in its continental and submerged portions.

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Geological map; volcanological evolution; caldera; Phlegrean Fields; Procida; Italy

1. Introduction

The Phlegrean Fields (PF) are part of the Phlegrean Volcanic District (PVD), the most widespread active volcanic system of the Mediterranean area, developed inside the Campanian Plain graben which includes the continental PF, Ischia and Procida islands (Orsi et al., 1996). The PVD formed following the opening of the southern Tyrrhenian basin, along with a system of regional transfer faults, that connects the Tyrrhenian bathyal plain to the continental areas (Acocella & Funiciello, 1999). The PVD developed since 200 Ky and is characterized by the volcanic fields of Ischia and PF, both formed by eruptive centers fed by trachytic-basaltic magmas and affected by regional caldera collapses following catastrophic explosive eruptions, occurred respectively around 60 and 39.3 Ky, and by marked resurgence phenomena (Sbrana et al., 2018).

In this paper, the evolution history of the PF and Procida Island (Figure 1) is described through a new volcanological map of both continental and marine areas. This map describes the volcanological and structural evolution of the volcanic field in its subaerial portions and in offshore environment. Despite the existing wide literature, a debate is still open about the submerged portions of the volcanic field and about the caldera structure and its evolution.

The map is based on previous geological surveys CAR.G (Geological CARtography, Servizio Geologico d'Italia) ISPRA Project, on absolute ages (De Astis et al., 2004; Di Renzo et al., 2011; Fedele et al., 2011; Orsi et al., 1996; Scarpati et al., 2013; Servizio Geologico d'Italia, 2012; Smith et al., 2011 and 2018) and on new volcanological data, deep and shallow well (−252< depth < −3040 m; Rosi & Sbrana, 1987) stratigraphic data, marine geology, geophysics. Furthermore, data on Roman-age archeological sites in PF marine sectors help in quantifying the more recent processes of subsidence or uplift that affect this high-risk volcanic area.

2. Evolutive history

The PF volcanic field includes monogenic volcanoes, littoral hydromagmatic tuff cones, ash rings, lava domes and lava flows, and deposits of Plinian destructive events dispersed over an area of about 300 km^2. Distal pyroclastic deposits older than 80 Ky east of PF (age between 157 and 300 Ky) are ascribed to the local center near Apennines's border rather than to PF (De Vivo et al., 2001). The PF volcanism starts in the Upper Pleistocene, with ancient volcanism dating back to 80 Ky. These latter are exposed at Monte di Procida and Procida Island, San Severino, Punta Marmolite, the eastern border of Piano di Quarto, Camaldoli, in the urban area of Naples, San Martino Hill (Orsi et al., 1996; Pappalardo et al., 1999; Scarpati et al., 2013), Mt. Echia, Castel dell'Ovo and Capodimonte, whereas the southern sector of PF is today submerged in the Pozzuoli Gulf (Figure 2). Penta Palummo, Monte Dolce-Pampano, and Miseno banks are the remnants of the ancient volcanic field (Mirabile et al., 2000; Pescatore et al., 1984; Rosi &

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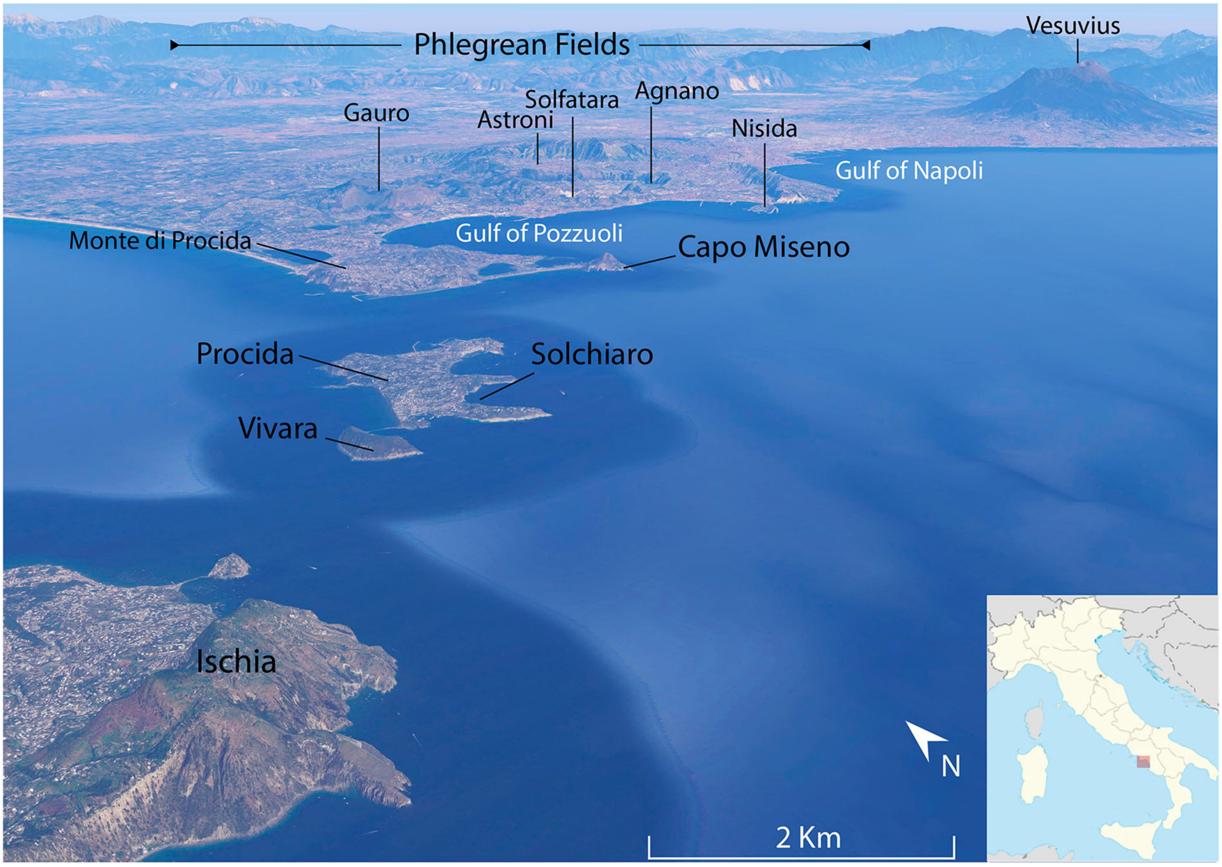

Figure 1. Phlegrean Volcanic District (Google Earth image), view from Ischia. In the foreground the Vivara tuff ring and Procida volcanic field, and in the background, continental Phlegrean Fields and Somma-Vesuvius volcano.

Sbrana, 1987). Around Procida, ancient, submerged craters and tuff cone craters are present (De Astis et al., 2004; Rosi et al., 1988). At 39.3 Ky ago (Figure 3), about 280 km^3 of trachyte (up to 300 Km^3 DRE in Scarpati et al., 2014 and references therein) erupted while a caldera formed: the Campanian Ignimbrite (CI) super eruption (Marianelli et al., 2006; Rosi & Sbrana, 1987) deeply modified the structure of the volcanic field and influenced its successive history.

The CI caldera depression was followed by the sea invasion. Deep drillings inside the caldera reveal the presence of the upper unit of CI – Breccia Museo (Rosi et al., 1983). These overlie pre-caldera lava domes in Mofete 2 and marine epiclastics in Licola1 wells, respectively. The volcanism of PF continues inside the caldera in a continental and marine environment. This is articulated in sectors collapsed by systems of faults (Figure 2). The outer fault system is well exposed in the continental portion of PF and traced southward by marine geology data (Mirabile et al., 1989; Pescatore et al., 1984 and 2000) and by seismic lines (Plate 2, line 67). The inner fault system is buried but well evidenced by high-resolution seismic surveys (Plate 2 lines 67-74-69, and Figure 4) offshore Pozzuoli, and by gravity data (Barberi et al., 1991; Rosi & Sbrana, 1987; Sacchi et al., 2014; Steinmann et al., 2016 and 2018). Post-caldera volcanism develops with tuff and scoria cones along the caldera border: few radiometric data indicate activity at 22.3 Ky for Trentaremi tuff ring and at 18.4 Ky for Torregaveta vent, Monte di Procida, and Solchiaro tuff ring, Procida island (Servizio Geologico d'Italia, 2012 and references therein). This preceded a large eruption occurring 14.9 Ky ago, during which the Neapolitan Yellow Tuff (NYT) formation was emplaced from the cluster of tuff cones of Posillipo, aligned from the southwest to the northeast, and from the Gauro tuff cone. The NYT activity was followed by collapses of tuff cone flanks (Bagnoli Plain, San Vito Plain, and Toiano Plain) and formation of nested calderas (Rosi & Sbrana, 1987).

After a rest period, volcanism was renewed near the eastern margin of the CI caldera with a cluster of explosive eruptions at La Pigna, Soccavo, Minopoli, Pianura, Pisani, San Vito, Agnano, La Pietra, Santa Teresa (I Epoch of Di Vito et al., 1999), and in the western sector of the caldera (tuff cones of Porto Miseno and Bacoli). In the southern sector, seismostratigraphic data indicate the growth of the Banco di Nisida tuff cone (Steinmann et al., 2018). At least 30 eruptions occurred between 12.9 and 10.9 Ky (Di Vito et al., 1999), associated with the onset of the resurgent dome of the CI caldera central area.

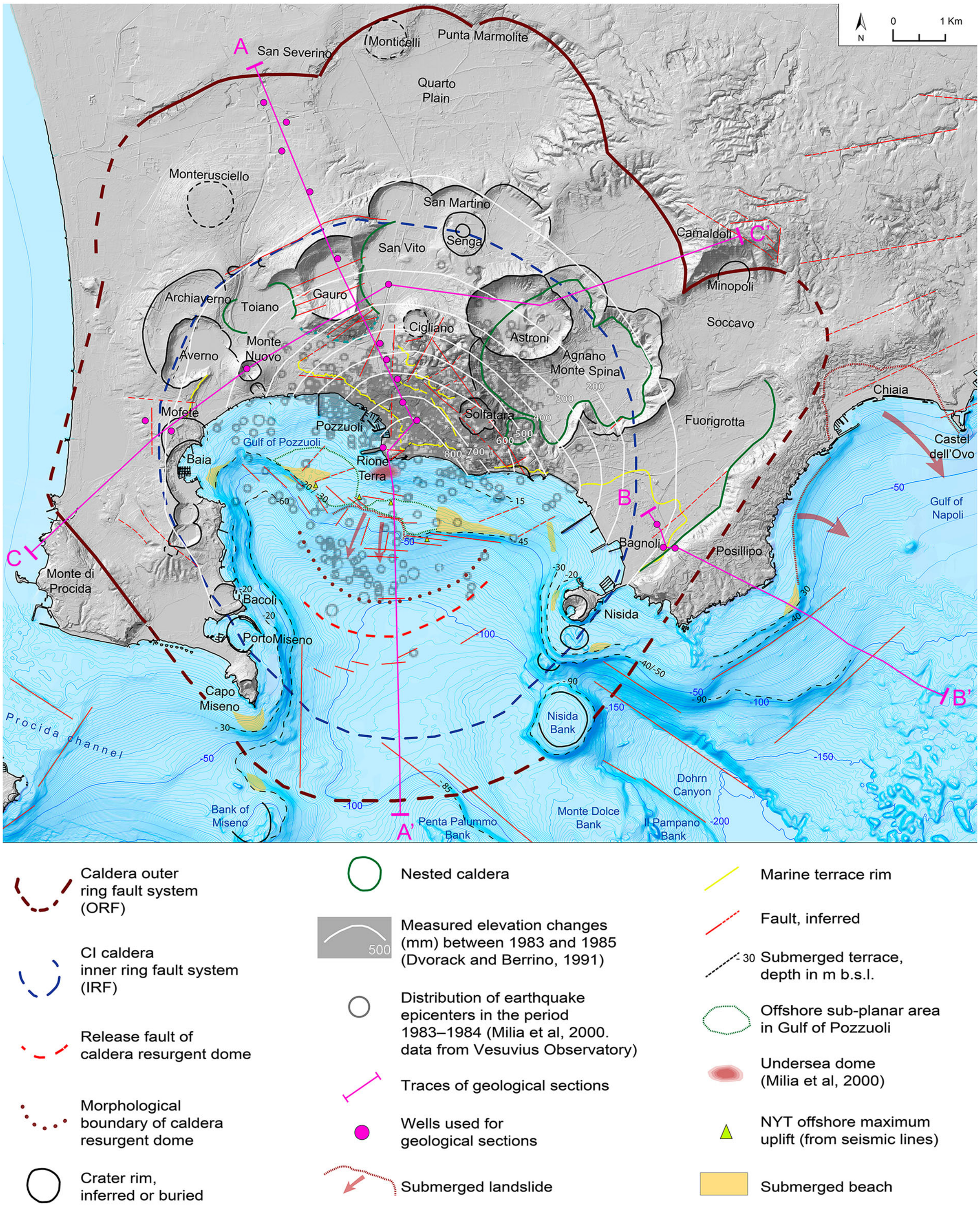

Figure 2. Structural sketch of continental Phlegrean Fields and Pozzuoli Gulf area. The map also contains the earthquake epicenters and the measured elevation changes (period 1983–1985) that show the center of the deformation located near Rione Terra tectonic pillar.

A second pause in volcanism of about 0.9 Ky preceded the activation of a second cluster of eruptions between 8.6 and 8.2 Ky (II Epoch of Di Vito et al., 1999). In this period, only five explosive events occurred in Agnano San Martino areas; in the western sector, Baia and Fondi di Baia ash rings developed.

A further period of volcanic stasis between 8.6 and 5.1 Ky is signaled by the widespread formation of a paleosol (Di Vito et al., 1999; Rosi & Sbrana, 1987) that preceded the III Epoch (Di Vito et al., 1999), characterized by 18 eruptions in the central area of the caldera as well as at Capo Miseno and Nisida. Volumes erupted in the central area are higher than in the western one (Di Renzo et al., 2011).

After a long stasis, volcanic activity was renewed with the Monte Nuovo eruption (1538 AD).

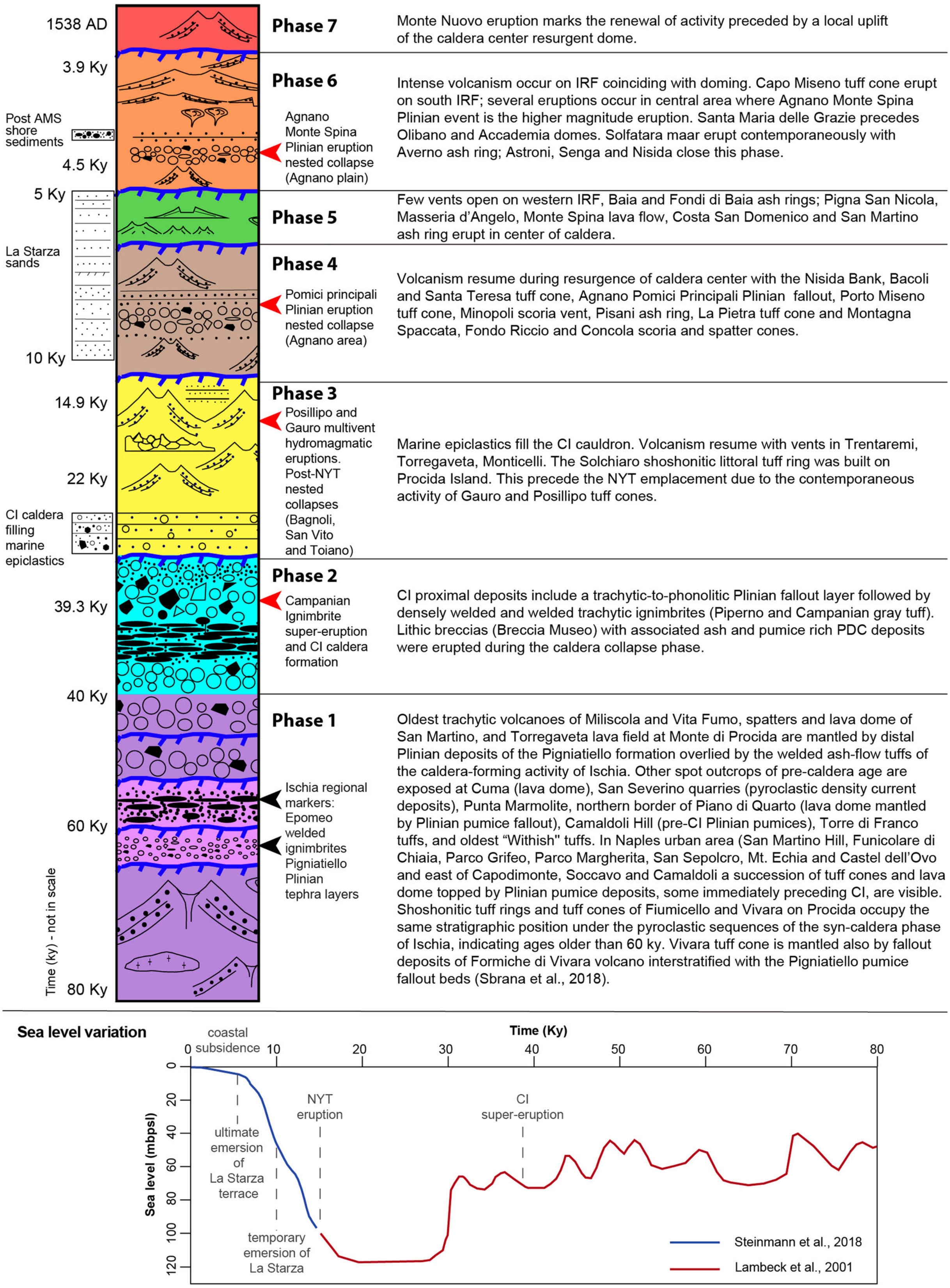

Figure 3. Simplified chronostratigraphic sequence of Phlegrean Fields. The seven phases of activity are based on defined periods of high volcanicity, caldera collapse and of stasis. In the lower part sea level variation modified from Lambeck et al. (2001) and Steinmann et al. (2018).

Bradiseismic crisis and strong fumarolic activity characterized the PF volcano state starting from the Monte Nuovo eruption to the present condition with a new uplift of the dome-shaped resurgent caldera central area (from Dvorak & Berrino, 1991; Milia et al., 2000).

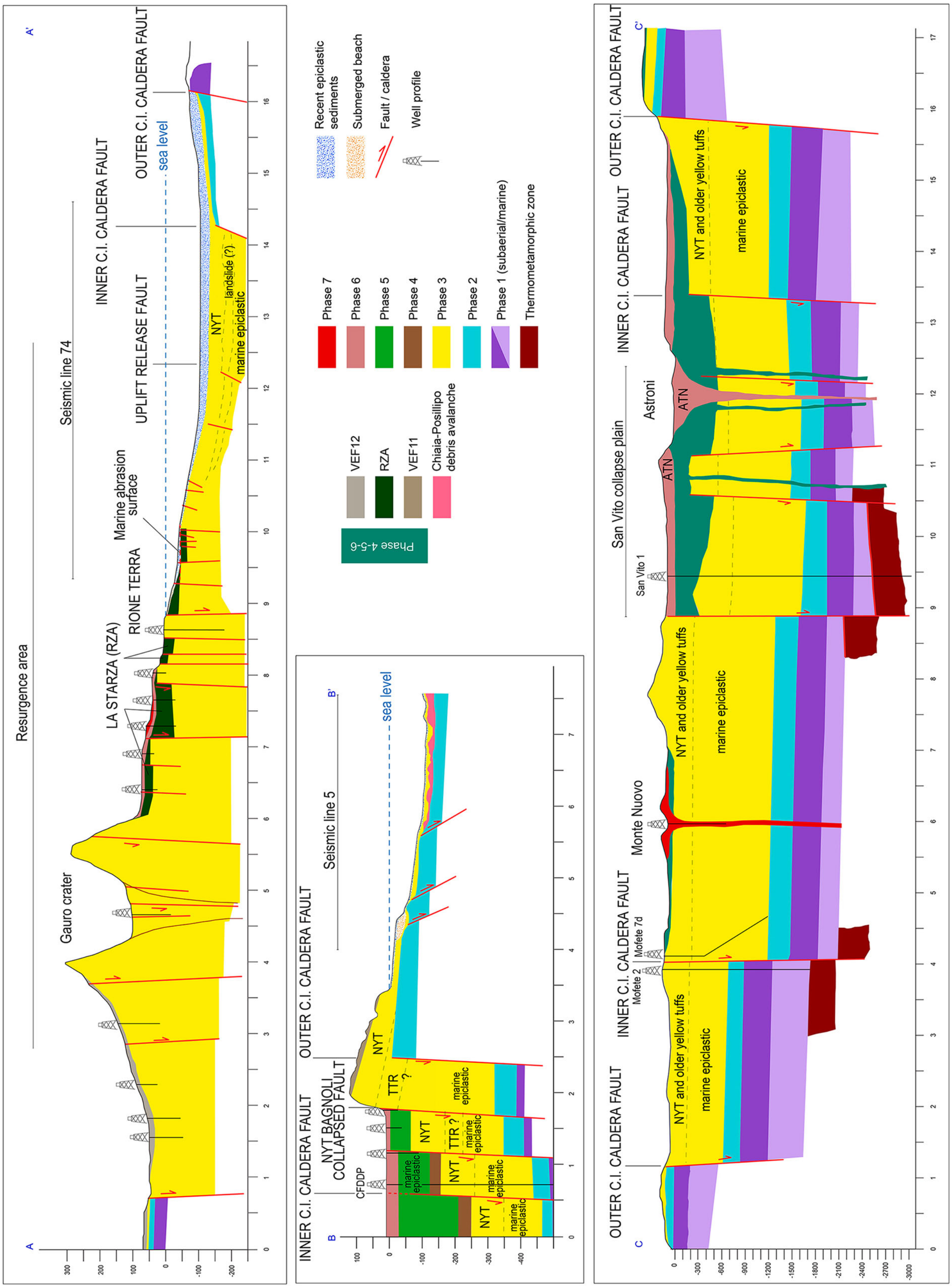

Figure 4. Geological sections. *Section AA′:* Gauro hydromagmatic tuff cone dominate the geological section. Phase 3 volcanics, marine sediments and epiclastics are involved in the doming area centered on Rione Terra. Vertical normal faults are arranged in a system of small horst and graben visible on Gauro tuff cone and in the dome-shaped marine area. *Section BB′*: Southeastern border of CI Caldera. Note the abrupt stratigraphic change between the southeast sector of PF where outside the caldera. In marine sub bottom deposits of the most voluminous eruptions predominate, the Campanian Ignimbrite deposits, sub surfacing in Gaiola area, and the overlying NYT. Inside CI caldera in Bagnoli post NYT collapsed (nested) area the stratigraphy shows a shallow succession of Phase 6 tephra overlying marine deposits and volcanics. The CFDDP well defines the positions of the outer and inner CI caldera ring faults inside Bagnoli plain. *Section CC′*: The location of the outer and inner ring faults is shown. Modified from Rosi & Sbrana, 1987.

Table 1. Estimated volumes of Campanian Ignimbrite caldera sectors and of NYT formation.

	Collapsed area (km^2)[a]	Vertical displacement (km)[b]	Cauldron volume (km^3)	Erupted Volumes (DRE)
CI Inner caldera (delimited by inner fault system)	70	1.5	105	80–300[c]
CI Intermediate caldera (delimited by inner and outer fault systems)	83	0.6	49.8	
NYT Bagnoli + S.Vito + Toiano calderas	18	0.3	5.4	30–54[d]

[a]Measured in main map.
[b]From deep wells and geological sections (Figure 4).
[c]Scarpati et al. (2014) and references therein.
[d]Orsi et al. (1992); Orsi et al. (1996) and Scarpati et al. (1993).

3. Materials and methods

The geological database used for the map design was collected during CARG field survey carried out from 2000 to 2010 at the 1:5,000 scale (Geological map of Italy, F 446-447 Napoli, 1:50,000, F 465 Isola di Procida, 1:25,000, F 464 Ischia, 1:25,000, ISPRA Geological Survey of Italy). During these projects multidisciplinary detailed data for volcanological evolution of PF were collected, including subaerial (240 km^2 of new surveys) and subaqueous geological surveys along profiles up to 30 m of depth, high resolution sparker seismic surveys (Plate 1 and 2; 9 km of sparker seismic lines), bathymetric data and stratigraphic wells drilled with continuous coring (650 m total drilling) to solve specific volcanological existing topics. Furthermore, key data for volcanotectonic structures reconstruction derive from results of 16 deep wells drilled for geothermal and scientific research (AGIP, 1987 and CFDDP, De Natale et al., 2016). Also, the georeferenced gravimetric map (AGIP, 1987; Berrino et al., 1998) was used to draw the inner CI caldera.

Volcanological offshore deposits are mapped interpreting available geophysical prospection (Plates 1 and 2) that cover the gulfs of Pozzuoli and Naples. The interpretation of the seismic facies is supported by previous studies (Sacchi et al., 2014; Steinmann et al., 2016 and 2018; Milia et al., 2000).

The map is based on the topographic background obtained combining Lidar DTM (1·1 m resolution, years 2009–2012) and the ORCA project DTM (5·5 m, years 2004–2005).

All these informations were elaborated and merged to produce the final map.

4. Results and discussion

The 57 lithostratigraphic units were organized in seven activity phases identified on the base on the updated absolute ages of eruptions, that defined periods of high volcanicity and of stasis (Figure 3). Relationships between the new proposed seven phases and the previous reconstructions of Phlegrean evolutive history (Di Vito et al., 1999) are shown in Figure 3 and in Plate 3. Furthermore, based on geological and geophysical evidence, a reconstruction of the PF caldera structural framework is proposed.

5. The PF caldera

The caldera is structured in three sectors: the outer, unaffected by collapse, and two inners, collapsed (Figure 2). Ring faults allowed for the differential sinking of the roof of the CI eruption magma chamber. The outer ring fault system (ORF) of CI caldera is traced along the outcropping collapse faults, cutting deposits older than CI from SW (Monte di Procida) to NE Camaldoli and E in the urban area of Naples (Figure 2 and Figure 4 sect. A–A’ and C–C’). In the southern marine portion of the volcanic field, ORF is traced in correspondence with the Miseno and Penta Palummo bank, Figure 4(A–A’) (Barberi et al., 1991; Pescatore et al., 1984; Rosi & Sbrana, 1987; Sacchi et al., 2014; Steinmann et al., 2016 and 2018). The SE sector of the PF volcanic field coincides with the Posillipo NYT vent alignments, and their offshore area is critical in defining the CI caldera. Seismic lines (Plate 1, lines 3-4-5) indicate that the CI deposits are at very shallow depths in the area and rise up under Posillipo hill rampart, as shown by the isobaths on the main map, while the offshore seismic lines exclude the presence of caldera fault systems (Plate 1). These data allow to place the ORF in this sector in the subsoil of Posillipo Hill, buried by Posillipo tuff cones deposits (Plate 1). In the south marine area, the inner ring fault (IRF) system runs from the Nisida volcanoes cluster to Capo Miseno (Figure 4 sect. A-A’). From Capo Miseno to Bagnoli Plain, in continental PF, IRF is buried under recent volcanics but could be drawn thanks to gravity data (Barberi et al., 1991; Pingue et al., 2000). The IRF delimitates the more collapsed area of the central sector of CI caldera that is about 1500 m (Table 1 and Figure 4) below the outer uncollapsed areas (Rosi & Sbrana, 1987). Geological and volcanological data, such as the volumes of NYT deposits (Orsi et al., 1996) that is lower (30–54 km^3 DRE, Table 1) than the calculated collapsed IRF volume (105 km^3, Table 1), and the evidence that NYT volcanoes are affected only by partial collapses, allow to exclude the occurrence of a caldera structure related to the volcanic activity during or after the NYT eruptions of the coeval Posillipo and Gauro volcanoes; conversely previous authors (Orsi et al., 1996 and references therein) consider this structure as due to NYT eruption.

The IRF plays a key role in the caldera evolution, as demonstrated by the distribution of the post CI caldera tuff cones (Mofete, Archiaverno, Monterusciello and Gauro), Phase 4 (Porto Miseno-Bacoli), Phase 5 (Baia and Fondi di Baia), and Phase 6 (Capo Miseno and Nisida among the others). Also, most of the hydrothermal circulation and active hydrothermal manifestations on land (Mofete and San Vito geothermal fields, Barberi et al., 1991; Rosi & Sbrana, 1987) and in the submerged portions of the caldera (Sacchi et al., 2014 and 2019; Steinmann et al., 2016 and 2018) are linked to the IRF.

A marked resurgence affected CI caldera starting about 12 Ky ago in its central continental and marine areas (Cinque et al., 1985; Marturano et al., 2018; Passaro et al., 2013; Sacchi et al., 2014; Steinmann et al., 2016; Steinmann et al., 2018). The dome-shaped densely faulted area is delimited in the Pozzuoli Gulf. The sub-bottom of the dome-shaped area is mainly represented by the Gauro tuffs (Plate 2). Northward on land, the resurgent area is marked by uplifted marine epiclastics forming the La Starza unit structured in paleo terraces. An array of vertical faults affects the Gauro tuff cone and the south marine areas, allowing the doming uplift, accompanied in apical area by extension with horst and graben structures (B-B' section in Figure 4).

The interaction between eustatic sea-level variations and PF volcanic evolution, resurgence, is highlighted by the presence of submerged flat abrasion surfaces traced in the Pozzuoli Gulf at different depths by bathymetric analysis and interpretation of seismic lines (Figure 2 and Plate 2).

The submerged remnants of the Roman archeological sites record sea-level variations over the last 2 Ky. A pronounced bending (Passaro et al., 2013) is observed between Pozzuoli (Rione Terra, Serapeo and Pozzuoli Roman Harbor) and Baia, coherent with the central doming of the caldera. The Pozzuoli area shows a positive uplift of more than 2 m, while Roman remnants in Baia sunk up to about 6/8 m b.s.l. Differences also exist between the external and internal sides of the caldera, as shown by La Gaiola (2-3 m b.s.l.) and Baia areas (8 m b.s.l.) on the main map.

6. Phase 1. Ancient volcanic field

The ancient volcanic field (Archiflegreo volcano of Rittmann, 1950) includes monogenic volcanoes, littoral tuff cones, ash rings, lava domes, lava flows, and explosive vents (Figure 3). Presently, these volcanoes outcrop outside the CI caldera collapse area. On land, starting from the Monte di Procida hills, four volcanoes are visible on the marine cliffs bordering the west side of the Monte di Procida (Figure 5). Other ancient volcanoes outcrop in Naples city (Figure 3), and on the east CI caldera border. The southern sector of the ancient volcanic field is submerged south of the Pozzuoli Gulf, except for the Procida Island area, were the trachytic tuff cone of Terra Murata and the complex of the trachytic tuff cone, spatter, and lava flow of Pozzo Vecchio are present below the Pigniatiello Plinian sequence (73–60 Ky) and CI deposits (Breccia Museo and Piperno).

7. Phase 2. Caldera forming - CI eruption

CI units (Figure 3) outcrop (Figure 6(A–C)) in areas inside Naples city, north (San Severino quarries and Quarto Plain) and east of PF on Camaldoli CI caldera borders (Pianura and Soccavo). Densely welded tuffs are present in the Pianura area (Piperno quarry outcrop and tunnels), at Monte di Procida (Acquamorta) and on Procida Island (Punta della Lingua, Figure 6 (D)). Breccias are diffused around the ORF and on Procida Island, where the Breccia Museo covers the oldest volcanoes, smoothing the pre-CI hilly morphology. The CI deposits are widely diffused in the south submerged portions of PF (Plate 1) and in the whole Campanian Plain. Erupted volumes (DRE) span from 80 to 300 km^3 (Scarpati et al., 2014 and references therein). This value agrees with the cauldron volume obtained for the collapsed sectors (delimited by inner and outer fault systems in the main map) (Table 1 and Figure 4).

8. Phase 3: Caldera filling and intracaldera activity – submarine toward the subaerial phase

Fossiliferous epiclastic tuffs (500–600 m thick), drilled by deep geothermal wells, partially fill the cauldron invaded by the sea (Rosi & Sbrana, 1987).

The eruptive activity was renewed (Figure 3) about 30 Ky ago with the emplacement of Verdolino tuffs (Pappalardo et al., 1999). A cluster of eruptions occurred around 18 Ky ago when an explosive vent opened on ORF at Torregaveta. A group of tuff cones developed along the IRF (Figure 3). This volcanic activity along ring faults was a prelude to and was closed by the NYT eruptions related to the activity of tuff cones activated on the ORF in the Posillipo area (Rosi & Sbrana, 1987) and of the Gauro tuff cone in correspondence of IRF. The eruptions of Gauro and Posillipo volcanoes (Figure 7) occurred at about 14.9 Ky (Deino et al., 2004; Insinga et al., 2004). Partial collapses delimited by vertical faults affect the east and west Gauro tuff cone flanks (Toiano and San Vito

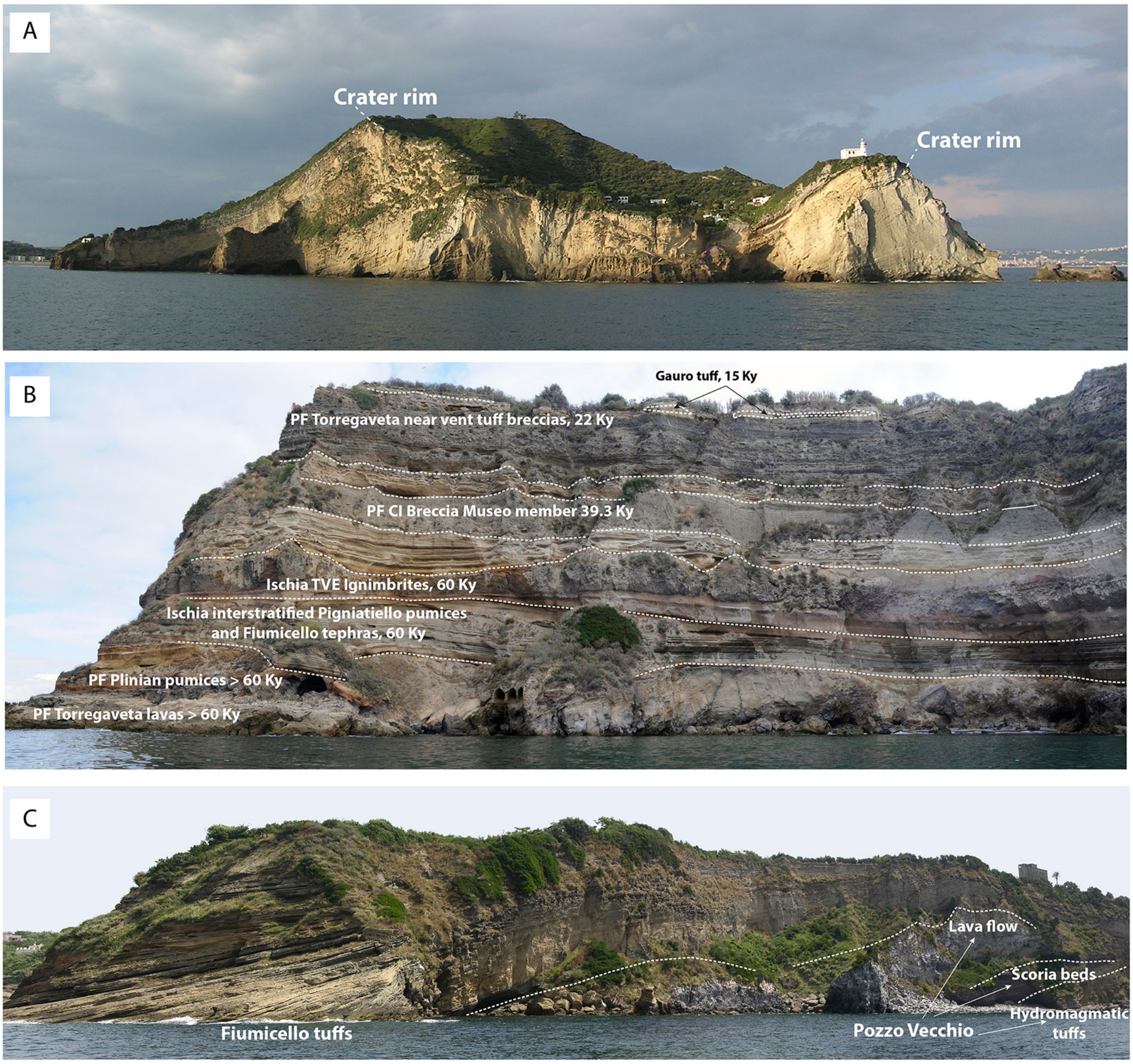

Figure 5. (A) Capo Miseno tuff cone, view from southwest. The marine cliff cuts the inner sections of the tuff cone. (B) The NW marine cliff of Monte di Procida: a complete record of the major explosive eruptions of Phlegrean Fields including Procida and Ischia deposits. (C) NW Procida marine cliff. Pozzo Vecchio volcano (age > 60 Ky) trachytic hydromagmatic yellow tuffs (bottom) vs magmatic effusive lava flow (top) mantled by Fiumicello shoshonitic littoral tuff ring ash and scoria rich, yellow, zeolitized tuffs.

nested calderas) and the north flank of the Posillipo tuff cone rampart (Bagnoli Plain nested caldera). Magma erupted volumes (DRE) were estimated in the range 30–54 km^3 (Scarpati et al., 2013).

A debris avalanche event preceded the NYT eruptions. In offshore of Posillipo and Chiaia, a hummocky area is evident in bathymetries between depths of −75 and −175 m (Plate 1). The detachment area is Chiaia on land amphitheater, and Posillipo Castel dell'Ovo submerged scar. Seismic lines provide evidence that this unit is covered by the NYT seismic unit and by the successive units of Phase 4 (Sacchi et al., 2019 and references therein), and that this unit covers the CI deposits. Therefore, we may speculate that an abrupt uplift of southeast PF reliefs precedes the NYT and that the high relief energy because of the very low sea level (−100 m below present sea level, Figure 3) may have induced the sector collapse and avalanching.

9. Phase 4: intracaldera activity – subaerial explosive subplinian and Plinian eruptions, scoria cones, ash cones, and tuff cones

The renewal of volcanism (I Epoch of Di Vito et al., 1999) occurred 12.9 Ky ago after about 2 Ky of inactivity of the caldera, during which a paleosol developed at the top of NYT (Plate 3); volcanism renewal (Figure 3) is accompanied by the marked resurgence of the CI caldera center. In marine areas of the caldera, several vents are highlighted by bathymetric data and by the interpretation of reflection seismic surveys, the Nisida Bank is probably the oldest one (Sacchi et al., 2014 and 2019; Steinmann et al., 2016 and 2018). It is located on

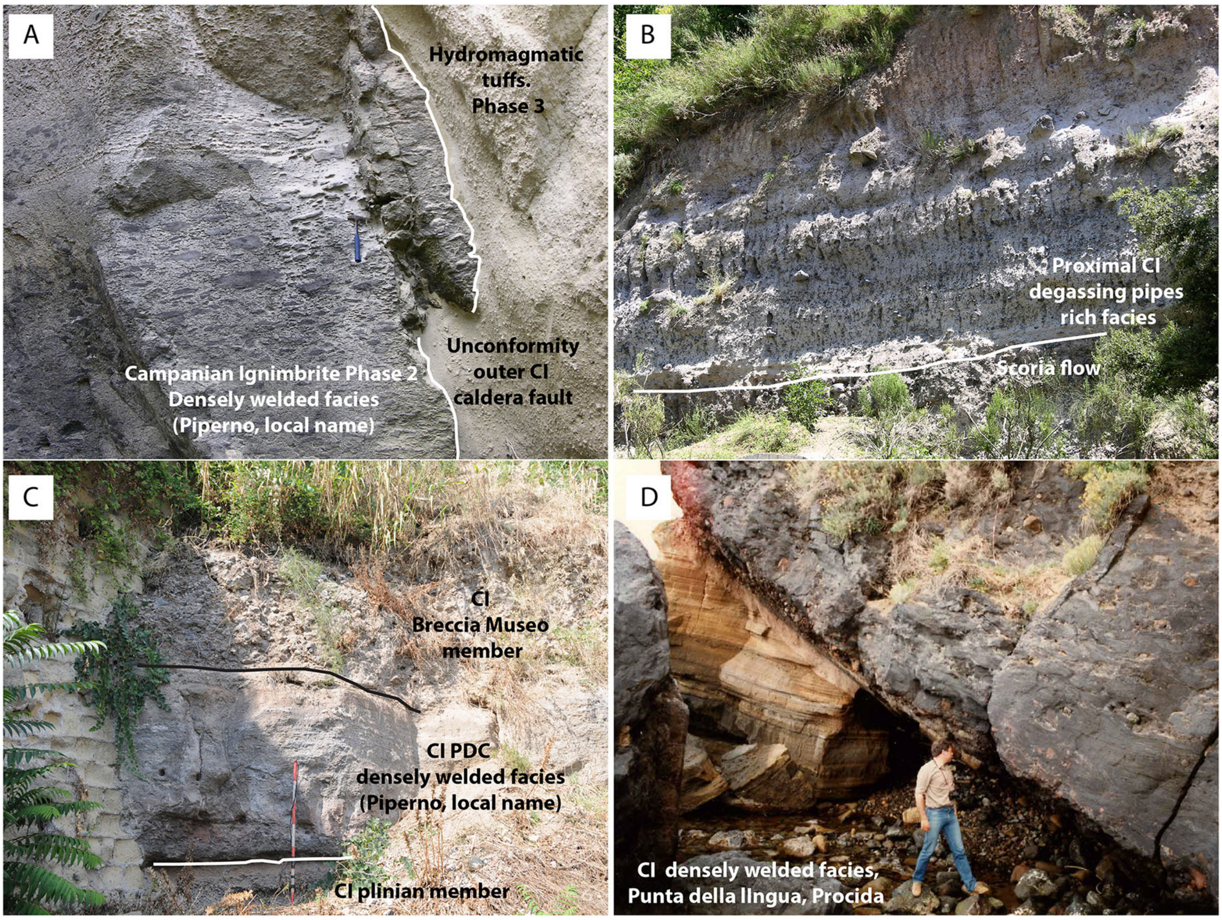

Figure 6. (A) Pianura, Piperno quarry. Proximal, near vent, densely welded facies of the Campanian Ignimbrite. The vertical unconformity in the photograph represents the outer vertical caldera ring fault. White ash and pumice layers are post-caldera deposits mantling ORF. (B) Valle del Verdolino, Soccavo, NW outskirts of Naples city. CI pyroclastic density currents. These facies develop along the CI ORF. (C) Downtown Naples: Vigna San Martino. Complete proximal sequence of CI eruption deposits. From the bottom pumice fallout layers followed by densely welded tuffs topped by coarse, lithic rich, fines depleted breccias, Breccia Museo Member of CI. (D) NE corner of Procida island. The picture shows a paleovalley cutted in Pietra Murata yellow tuff volcano deposits, filled by very densely welded facies of CI (black layer) overlying a characteristic pinkish bed of partially welded ashes and ground layer type deposits. The densely welded ignimbrite is topped by Breccia Museo member.

the ORF (Figure 2) and appears shaped by a submarine abrasion surface at −90 m. On the western side of the caldera, Bacoli and Porto Miseno tuff cones activate in correspondence with the IRF (Figure 2). Near the center of the caldera, the latitic tuff cones of La Pietra and Santa Teresa grow.

Subsidence (following the NYT eruptive climax) and rising (following the last glacial minimum) of the sea level (Figure 3) determined the formation, in the central portion of the caldera, of marine epiclastic deposits constituted by fossiliferous sands, derived by reworking of pyroclastics in a marine transitional environment, that lies directly above the Gauro tuff cone deposits. These epiclastics are mapped as La Starza units (heights up to 60–100 m a.s.l., recording uplift occurred during updoming of the CI caldera center). The dome-shaped structure is centered on Rione Terra at Pozzuoli (Cinque et al., 1985; Marturano et al., 2018; Rosi & Sbrana, 1987): a tectonic pillar possibly pushed up by shallow magma bodies, apophysis of the shallow magma chamber. The southern side of the caldera center doming is well visible in the morphology of the caldera sea bottom in the Pozzuoli gulf (Passaro et al., 2013).

10. Phase 5: intracaldera activity – ash and tuff rings, littoral tuff cones

Few trachytic eruptive centers (Baia and Fondi di Baia ash cones, Bacoli tuff cone) appeared active 9.7–8.6 Ky ago (II Epoch of Di Vito et al., 1999) in the west side of the caldera. In the central area of PF, Pigna San Nicola, Masseria d'Angelo, Monte Spina lava flow, Costa San Domenico and San Martino ash ring, indicate a clear dichotomy in eruptive areas (Figure 3). A phase of emersion was observed in La Starza unit (Isaia et al., 2019), suggesting a pulse in the resurgence of the caldera floor.

11. Phase 6: Intracaldera Holocene recent activity

After 3 Ky of rest volcanism was renewed with the opening of 12 vents (III Epoch of Di Vito et al.,

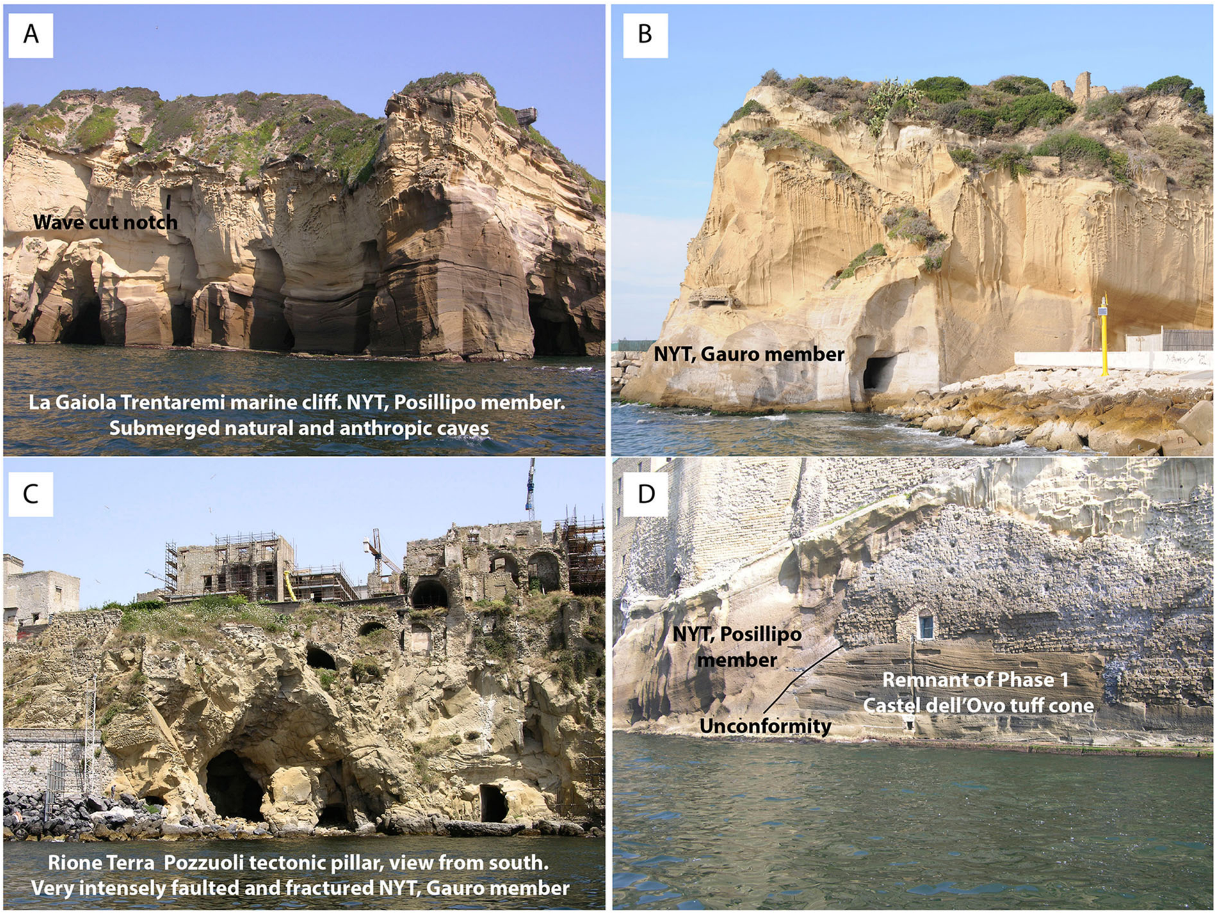

Figure 7. NYT: Posillipo tuff cones cluster and Gauro tuff cone. (A) La Gaiola Trentaremi marine cliff. Hydromagmatic cross stratified, dune bedded yellow zeolitized tuffs of NYT, Posillipo member. Several natural caves and quarries of construction material from the Roman and later periods were partially invaded by the sea due to subsidence. (B) Torregaveta. Neapolitan Yellow tuffs, Gauro member. Hydromagmatic cross stratified deposits of dilute turbulent pyroclastic density currents (surges) piled up on the outer CI caldera border. (C) Rione Terra tectonic pillar is the center of the CI resurgent dome and the area of maximum deformation in the more recent bradeismic crisis affecting caldera 1970, 1984 and present crisis. (D) Castel dell'Ovo outcrops. The unconformity between old yellow tuffs of the Phase 1 ad NYT, Posillipo member, Phase 3, overlying oldest deposits, is visible.

1999) in correspondence of the IRF (Figure 3). The Agnano Monte Spina Plinian eruption was followed by a caldera collapse causing the Agnano minor nested caldera and a general subsidence allowing the sedimentation of the Pozzuoli marine epiclastic units (4.6–4.5 Ky) (Isaia et al., 2009). The subsidence was followed by the start of a new cluster of eruptions and the occurrence of a new uplift of about 25 m of the caldera center, testified by the uplift of shore sediments between La Pietra area and Pozzuoli. The emplacement of the latite scoria cone of Santa Maria delle Grazie precedes the effusion of the exogenous trachytic lava domes of Olibano and Accademia. Afterward, the Solfatara maar deposits (Figure 8) interstratified with tephra of the Averno ash ring (Isaia et al., 2009), indicates contemporaneous multivent activity inside the caldera. After a short interval, Astroni polygenic ash ring erupts with seven explosive events. Its deposits include pumice fallout and cross-bedded stratified ashes. A scoria cone and a small lava flow closed the activity inside the crater. The Senga volcano formed by a nice set of concentric rim craters, and the Nisida littoral tuff cone placed along the ORF, closed Phase 6.

12. Phase 7: Monte Nuovo to present

After 2.3 Ky of rest, activity was renewed in 1538 AD with the Monte Nuovo eruption (Figure 3). The eruption was preceded by a pronounced uplift of the NW side of the resurgent area that started in 1502 AD and increased two years before the eruption (Orsi et al., 1999). The new vent opened in an area of diffuse hydrothermal manifestation at the western termination of the La Starza uplifted terrace. After the Monte Nuovo eruption, several bradyseism cycles occurred (Lima et al., 2009), inducing a cumulative uplift of about 3 m from 1902 up to today. The Monte Nuovo event seems to mark a new phase of activity inside the caldera.

13. Conclusions

The evolutive history of the PF subdivided in seven phases makes easier the reading of the map as well

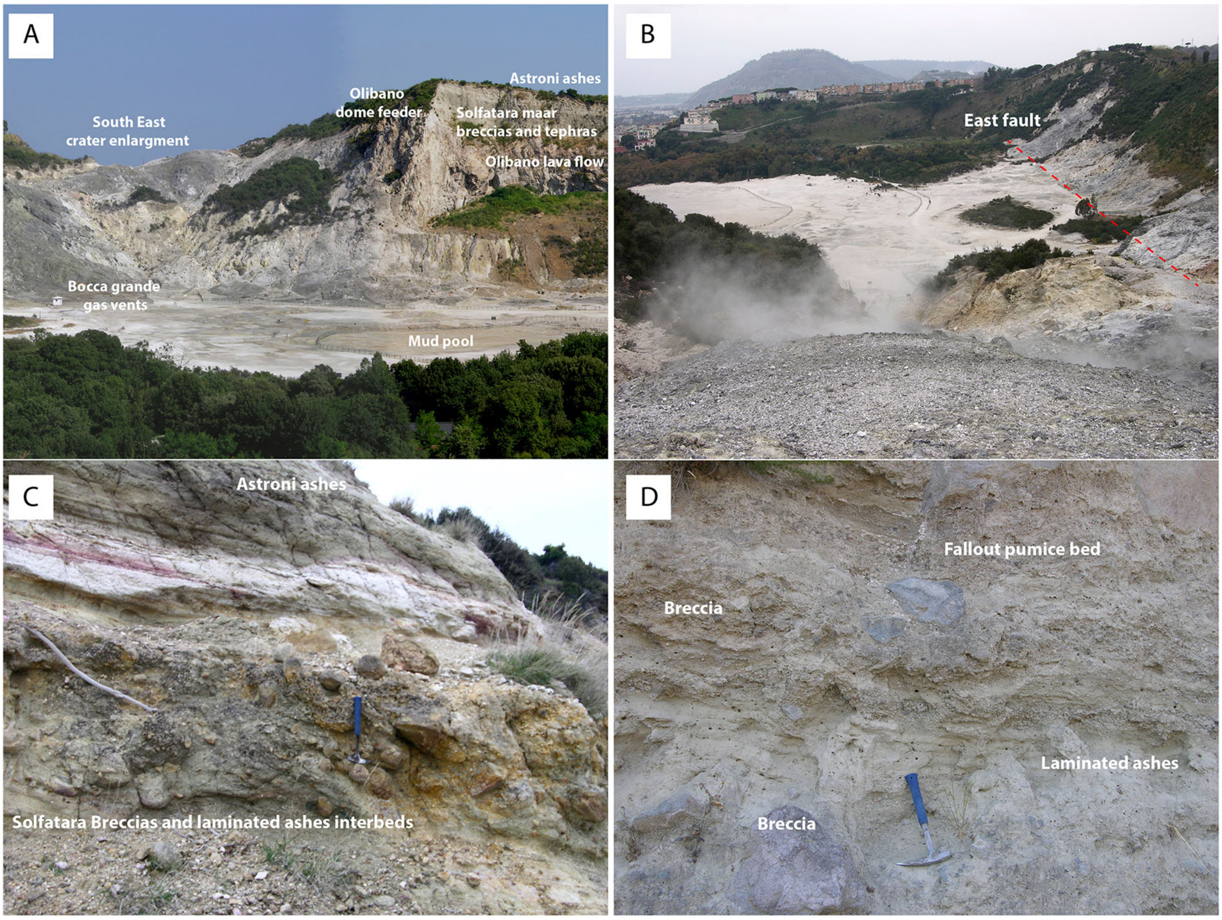

Figure 8. Solfatara maar. (A) Image of south-east inner wall of maar. Inside crater are evidenced by the characteristic mud pool (Fangaia) and Bocca Grande fumarole vents. (B) NE crater inner wall. The fault controlling the hydrothermal alteration (advanced argillic facies) and fumarole vents is traced in red. (C) Pyroclastic breccias poor in juvenile fraction on the southeast rim topped by Astroni ashes. (D) Particular of the maar sequence at the top of Solfatara western rim.

as the comprehension of volcanological evolution, that is mainly linked to the CI caldera collapse occurred through two main ring faults (ORF and IRF, Figure 2).

The Posillipo and Gauro tuff cones (i.e. the source vents of the NYT formation, erupting contemporaneously) are affected only by flank partial collapses (San Vito, Toiano and Bagnoli nested minor calderas). This fact, and the comparison between the erupted volumes during the CI super-eruption, the PF caldera volumes, and the magma volumes erupted during NYT (having about an order of magnitude less, Table 1) supports the conclusion that the inner more collapsed area, delimited by IRF, was linked to the CI caldera instead to a NYT caldera.

Clusters of volcanoes were active along the ring faults. ORF drove volcanism mainly in Phase 3 (Torregaveta, Monticelli, Trentaremi, Nisida Bank, and Posillipo tuff cones cluster) and sporadically in Phase 4 (Minopoli). Volcanism of Phase 3 (Gauro tuff cone) and mainly of Phases 4, 5 and 6 is linked to the IRF in the western, north-west and south caldera sectors.

Resurgence of the caldera started during Phase 4. The structures of the central resurgent dome in Pozzuoli Gulf and on land in Gauro sector are arranged in small tensional horst and graben (Figure 4, sect. A-A'). In Pozzuoli gulf, the resurgent dome is affected by a wide marine abrasion surface that develops at different depths with the western shallower than the eastern one (Figure 2 and main map). This possibly reflects the larger volume of magma emitted in the central-eastern volcanic cluster of vents during Phases 4, 5 and 6.

The new volcanological map with the reconstruction of the volcano-tectonic structures in the whole volcanic field furnishes a homogeneous model linking the on-land volcanic areas with the submerged ones.

The map furnishes also key information for the defining of the global volcanic hazard and risk for the whole area and makes it clearer the resurgence structural model (doming) of the caldera center, shedding light on system of faults active in bradeisismic crisis.

Furthermore, the importance of ring faults in the uprise of magmas and in vent openings is highlighted in the main map and represents a key-point for the hazard evaluation of the caldera.

Software

All information was managed in a geographical information system (ESRI ARCGIS® 10.6), producing several thematic layers. Adobe Illustrator® CC 2018 was used to produce the layout of the final map.

Geolocation information

The study area is located in Italy – Campania Region, and includes Phlegrean Fields and Procida Island. Map extension: 40°45′00″ N, 14°00′00″ E; 40°54′00″ N, 14°15′00″ E.

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Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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