Bollettino di Geofisica Teorica ed Applicata Vol. 61, n. 3, pp. 333-342; September 2020
DOI 10.4430/bgta0315

Resurgent dome faults in the offshore of the Campi Flegrei caldera (Pozzuoli Bay, Campania): preliminary results from high-resolution seismic reflection profiles

J. Natale[1], L. Ferranti[1,2], C. Marino[1] and M. Sacchi[3]

[1] *Dipartimento di Scienze della Terra, dell'Ambiente e delle Risorse, Università Federico II, Napoli, Italy*

[2] *Istituto Nazionale di Geofisica e Vulcanologia (INGV), Roma, Italy*

[3] *Istituto di Scienze Marine (ISMAR), Consiglio Nazionale delle Ricerche (CNR), Napoli, Italy*

(Received: 27 March 2019; accepted: 7 January 2020)

ABSTRACT This paper presents a detailed reconstruction of faults associated with volcano-tectonic activity within the Neapolitan Yellow Tuff caldera (Campi Flegrei, Campania), based on the analysis of very high-resolution seismic reflection profiles in the Pozzuoli Bay. The eruption of the Neapolitan Yellow Tuff and the ensuing collapse of the caldera occurred ~15 kyr and was followed by intra-caldera eruptive activity and resurgence of a central dome. The seismic lines have been calibrated with gravity cores in the upper part of the stratigraphic succession, whereas the position of the Neapolitan Yellow Tuff at higher depths has been inferred by correlation with published seismic reflection data. This reconstruction allowed a tentative chronostratigraphic correlation of intra-caldera seismic reflectors, which involves alternating marine sediments and volcaniclastic deposits from the main intra-caldera eruptions, with the last 15 kyr stratigraphy established on land. We focus here on the apical faults of the resurgent dome, whose throw varies from the sub-metre to several metres scale. The motion on these faults occurred in the last ~5 kyr and was coeval to an intense volcanic activity reported on land. Based on the fault orientation and the age of offset reflectors, at least two sets of high-angle faults that moved at different times are distinguished.

Key words: volcano-tectonics, high-resolution seismic reflection profiles, caldera resurgence faults, Campi Flegrei.

1. Introduction

Campi Flegrei is a ~14 km wide caldera located in a very urbanised area that hosts more than one million people, including the western part of Naples (Campania, southern Italy). The northern, eastern, and western sectors of the caldera are above sea level and are characterised by the presence of scattered cones, craters, and, subordinately, lava domes. The southern sector, which represents over one-third of the caldera depression, is submerged beneath the Pozzuoli Bay and includes part of the resurgent dome developed inside the caldera (Figs. 1a and 1c).

Since the 1970s, and more definitely in the last decade, the submerged part of the caldera has been investigated through bathymetric and seismic reflection surveys. These researches unveiled

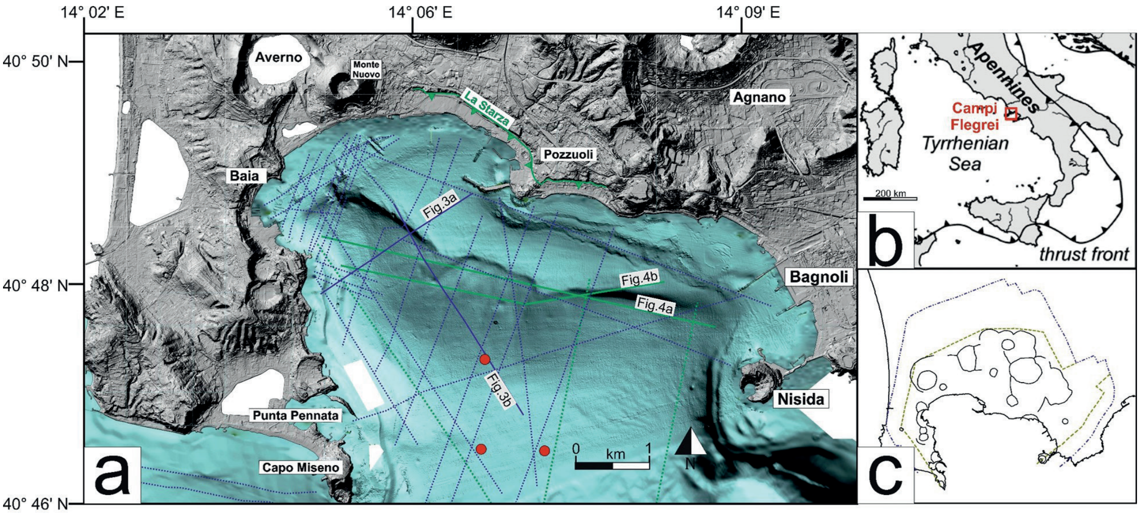

Fig. 1 - a) Seismic grid and core location on a high-resolution Digital Elevation Model of Campi Flegrei (Passaro *et al*., 2013; Vilardo *et al*., 2013). Dotted blue and green lines are Seistec and sub-bottom chirp high-resolution profiles, respectively. Solid lines are profiles shown in this paper. Red filled circles: gravity cores used for stratigraphic calibration. b) Regional location of study area. c) CI (blue) and NYT (yellow) caldera boundaries, post 15 kyr volcanic outlines (modified after Vitale and Isaia, 2014).

the salient geological features underneath the Pozzuoli Bay (Colantoni *et al*., 1972; Pescatore *et al*., 1984; Milia, 1998; Milia *et al*., 2000; Aiello *et al*., 2012, 2016; Sacchi *et al*., 2014; Steinmann *et al*., 2016, 2018). However, many details of the volcano-tectonics structures active in the post-caldera evolution (last 15 kyr) are still poorly defined.

In this work, we use very high-resolution seismic reflection profiles to reconstruct the geometry and relative timing of structures related to volcano-tectonic activity in the resurgent dome area during the last 5 kyr. Results contribute to a detailed reconstruction of the recent structural evolution of the Campi Flegrei caldera.

2. Geological setting

Campi Flegrei caldera is a volcanic field that hosts a nested caldera complex in the central part of the Campanian Plain, on the Tyrrhenian margin of the southern Apennines (Figs. 1b and 1c) (Vitale and Ciarcia, 2013; Vitale and Isaia, 2014). This restless caldera hosts more than 1 million people, including the western part of the densely urbanised town of Naples. The onset of volcanic activity in this area is dated back to ~80 kyr, and in the last 40 kyr at least three large [>VEI (Volcanic Explosivity Index) 6] ignimbrite-forming eruptions have occurred (Lirer *et al*., 1987; Orsi *et al*., 1996; Albert *et al*., 2019). The last large eruption emplaced the Neapolitan Yellow Tuff (NYT), which produced a major caldera collapse (Fig. 1c) at 14.5±0.4 kyr (Orsi *et al*., 1992; Scarpati *et al*., 1993; Deino *et al*., 2004; Galli *et al*., 2017). Following the NYT eruption, several phases of intra-caldera volcanic activity took place and clustered in time (Di Vito *et al*., 1999; Bevilacqua *et al*., 2016). Periods of frequent eruptions are documented at 14.3-10.6 kyr (Epoch

1); 9.6-9.1 kyr (Epoch 2); 5.5-3.5 kyr (Epoch 3) and occurred in different sectors of the caldera over time (Smith *et al*., 2011; Bevilacqua *et al*., 2016).

Significant ground deformation episodes accompanied the volcanic activity and unrests, and they are well documented for the historical and recent times (Rosi and Sbrana, 1987; Dvorak and Berrino, 1991; Di Vito *et al*., 1999, 2016; Isaia *et al*., 2009). The evidence of long-term ground uplift is testified by the La Starza marine terrace outcropping at 40 m a.s.l. west of Pozzuoli (Fig. 1a), which embeds marine and continental pyroclastic successions aged between 11.8 kyr B.P. and 1538 C.E. (e.g. Isaia *et al*., 2019, reference therein).

The occurrence of Roman structures along the coastline, such as breakwaters and piers, at a depth of 10 m b.s.l. (Passaro *et al*., 2013) indicates that subsidence has occurred in the area over the last 2 kyr. This subsidence was interrupted by two-century-long uplift preceding the A.D. 1538 Monte Nuovo eruption (Di Vito *et al*., 1987, 2016; Dvorak and Gasparini, 1991; Morhange *et al*., 2006). Since the 1950s, a series of rapid unrest episodes produced, alternating with periods of subsidence, a cumulative uplift of ~4 m (Del Gaudio *et al*., 2010; Chiodini *et al*., 2015).

The structural expression of post-caldera activity was studied in details on land (e.g. Vitale and Isaia, 2014; Vitale *et al*., 2019). Some general structural information exists in the sector of the caldera submerged beneath the Pozzuoli Bay (Colantoni *et al*., 1972; Sacchi *et al*., 2014; Steinmann *et al*., 2016).

The high-resolution bathymetric map of the Pozzuoli Bay (Passaro *et al*., 2013) shows that the underwater area can be divided into two sectors (Fig. 2). The central sector encompasses part of the Campi Flegrei resurgent dome, and the peripheral area includes the ring fault zone (Sacchi *et al*., 2014). The two morpho-structural domains are separated by the Epitaffio and Bagnoli submarine valleys to the west and the east, respectively (EV and BV in Fig. 2). The south-convex shape of the slope in the central part of the bay reflects the southern flank of the uplifted dome (Figs. 1a and 2a). An inner shelf is carved into the submerged dome and is limited seawards

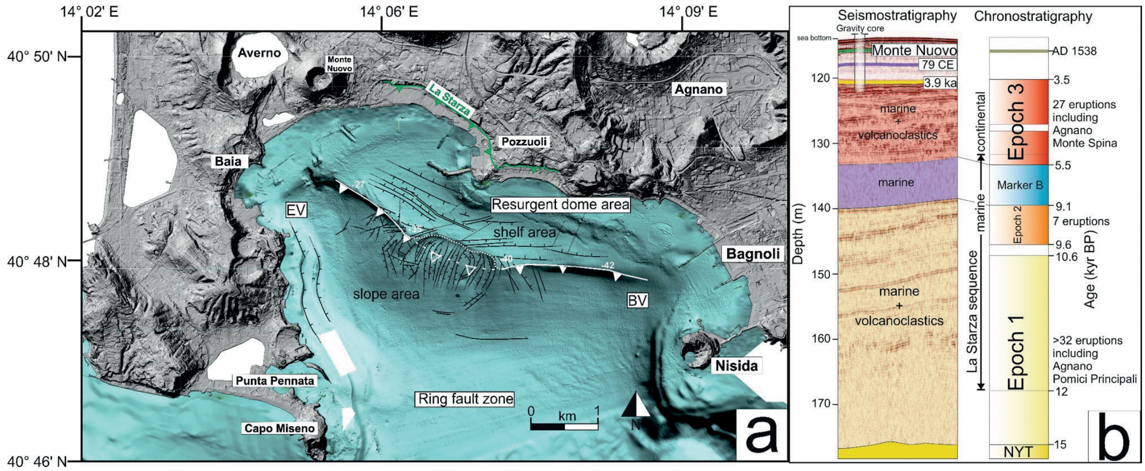

Fig. 2 - a) Structural map of the resurgent dome area in the Pozzuoli Bay. Black lines indicate faults, barbs on the downthrown block. Dotted black lines for inferred faults. EV, BV: Epitaffio and Bagnoli submarine valleys, respectively. White solid line with triangles indicates the shelf break, with depths. Dashed lines, reconstructed geometry of shelf break prior to NNE fault set activity. b) Reconstructed seismostratigraphy with horizons calibrated with gravity cores from Sacchi *et al*. (2014). Comparison with on-land chronostratigraphy and La Starza marine sequence is shown.

by a shelf break at depths between ~20 and ~40 m b.s.l. (Fig. 2). The development of the inner shelf likely resulted from the interaction between sea-level rise, coastal dynamics, and ground deformation processes (e.g. Hernandez-Molina *et al.*, 2000).

The first detailed reflection seismic survey in the Pozzuoli Bay was performed by Colantoni *et al.* (1972) during the 1970-1972 volcanic unrest. This study relied on a homogeneously spaced NW-SE/ENE-WSW line grid, which allowed identifying for the first time two main fault sets within the dome. More recently, Sacchi *et al.* (2014) mapped a dense array of ~NE-SW striking faults across the shelf-slope transition. Other authors (e.g. Capuano *et al.*, 2013; Di Napoli *et al.*, 2016) proposed that the bathymetric expression of the shelf edge that runs from Baia to Nisida (Figs. 1a and 2a) corresponds to a fault system composed of NW-SE and E-W segments. Orsi *et al.* (1999) suggested that a structural alignment with an orientation similar to the shelf edge (Mofete-Banco di Nisida alignment) hosted part of the seismic activity that occurred during the 1982-1984 bradyseismic crisis. On the base of boundary analysis of gravity data, Florio *et al.* (1999) identified an E-W striking fault along the coast east of Pozzuoli and two NW-SE striking faults broadly coinciding with the shelf edge.

3. Materials, methods, and stratigraphic frame

We analysed seismic profiles acquired by ISMAR-CNR of Naples (Fig. 1), and namely: a) high-resolution uniboom profiles (Seistec_2013 data set); b) sub-bottom chirp profiles (Marisk_2010 data set). The uniboom profiles presented in this work were acquired using the IKB-Seistec profiler, designed for collecting high-resolution data in shallow water environments (Simpkin and Davis, 1993; Mosher and Simpkin, 1999). Processing and interpretation of the profiles were performed using the GeoSuite AllWorks software package. Signal penetration was found to exceed 300 ms (two-way travel time). Vertical resolution reached up to 0.1 m near the seafloor.

The shallowest seismic-stratigraphic interval has been calibrated using three marine gravity cores (Fig. 1) published by Sacchi *et al.* (2014), which reach a maximum depth of ~6 m. Gravity cores (Fig. 2b) contain key horizons that can be correlated, from top to bottom, to: i) 1538 C.E. Monte Nuovo tephra; ii) 79 C.E. tephra (Somma-Vesuvius) mixed with 60 C.E. Cretaio eruption (Ischia Island); iii) a tephra dated at ~3.9 kyr correlated to Nisida or Capo Miseno. The reflectors correlated by Sacchi *et al.* (2014) to the cored sequences have been recognised in our seismic lines, allowing us to use them for stratigraphic calibration of the seismic units discussed in this study. Based on core data, we interpret underlying reflectors characterised by high-amplitude, high-frequency continuous reflections as tephra intercalated within marine sediments. The occurrence of sand and silt alternating with ash/pumice/lithic layers is responsible for significant variation of acoustic impedance that often produces strong reflection amplitudes. On the other hand, transparent to chaotic reflections are attributed to successions of prevailing marine deposits that contain minor and laterally discontinuous volcanoclastic units (Fig. 2b).

Based on the alternation of these two prevailing seismic *facies*, we reconstructed the chronostratigraphy of the caldera infill sequence (Fig. 2b). The base of the caldera infill was constrained by the depth of the NYT drawn from published multichannel seismic profiles (Steinmann *et al.*, 2016, 2018). The stratigraphic reconstruction was performed through correlation of the strong-amplitude reflectors to tephra (both ash fall and pyroclastic density currents) of the most significant eruptive events in the Campi Flegrei (Orsi *et al.*, 2004; Neri *et al.*, 2015). The reflection-free intervals, characteristic of sand-to-silt marine sediments with subordinate or lacking volcanoclastic material, were hence deposited during times of volcanic quiescence.

In order to estimate fault displacement and the thickness of seismic units, two-way travel (TWT) time profiles were converted to depth using an average velocity of 1650 m/s, which is representative for shallow mostly unconsolidated pyroclastic material (Sacchi *et al.*, 2014 and references therein).

4. Structural analysis results

The presented volcano-tectonic reconstruction relies on the identification of seismo-stratigraphic and geomorphological markers. The most important and widely distributed seismic stratigraphic marker interval is herein labeled "B" (Fig. 2b). It is characterised by a transparent *facies* with high-amplitude basal and top reflectors. This marker shows a thickness tapering from ~10 m in the deeper part of the bay, to ~1 m on the edge of the shelf, increasing again up to 3 m beneath the inner part of the shelf. Locally, this level thickens in bathymetric lows such as channels. Based on its seismic character, we interpret this interval as a predominant marine sequence without a significant contribution from primary tephra. Considering its stratigraphic position, relative to the NYT unit and the shallow cored sequence, marker B is correlated to the sequence emplaced during the non-eruptive period separating Epoch 2 and 3 [9.1 to 5.5 kyr: Smith *et al.* (2011)].

This 3.6 kyr long quiescence is marked within the La Starza terrace on land by a few metres thick sequence of fossiliferous marine sands without primary volcanic material (Isaia *et al.*, 2019; Vitale *et al.*, 2019), resting above the regionally distributed "Paleosol B" (Di Vito *et al.*, 1999). These marine deposits represent the outcrop analogous of seismo-stratigraphic sequence B.

Marker B was not identified in previous papers and was included within larger seismic units as shown in Table 1. On the basis of the high-resolution seismic profiles, we were able to define it in more details.

Table 1 - Comparison of published seismic units and ages for marker B defined in this work.

This work	Colantoni *et al.*, 1972	Milia *et al.*, 2000	Sacchi *et al.*, 2014	Steinmann *et al.*, 2016
Marker B	Horizon C	included in G2	included in U3	included in M3
9.1-5.5 kyr	no estimation	12.0-4.0 kyr	6.6-2.0 kyr	8.0-5.0 kyr

We divided the structural framework of the submerged part of the resurgent dome into two domains based on the different orientations of faults. A northern array of normal faults with E-W to WNW-ESE strike (set 1) is found beneath the shelf facing Pozzuoli for a total length of ~4 km and a width of ~1 km (Figs. 2a, 3a, and 3b). These faults have average dips between 70° and 80° (Fig. 3) and displace both to the north and the south with individual throws in the order of ~1 m, forming minor horst and graben-like structures. Based on the offset of marker B and younger reflectors, the north-dipping fault set achieves the larger cumulative throw. However, the presence

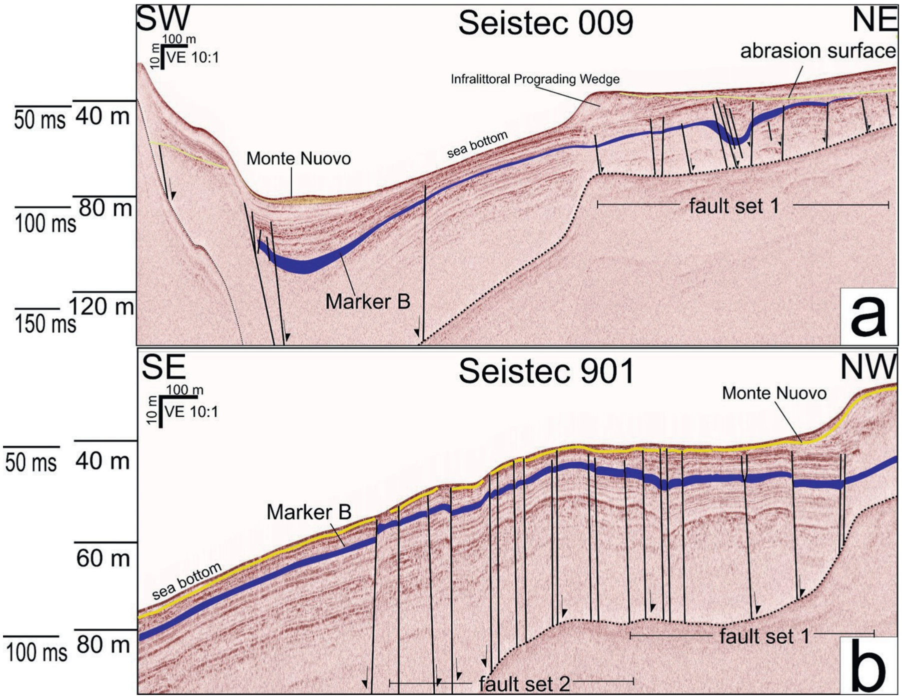

Fig. 3 - a) ~SW-NE trending Seistec line 009 showing the Baia fault system to the west, and ~E-W oriented faults to the east. See map in Fig. 1 for location. Note the ~4.0 kyr abrasion surface sealing the E-W faults. b) NW-SE oriented Seistec line 901 showing the younger motion of both fault sets cutting Monte Nuovo horizon and locally the seafloor. Black dotted line: multiple reflection.

of ~N-S trending faults is not excluded as their identification could have been biased by the mainly ~N-S trend of the studied profiles, which allow easier mapping of orthogonal trending structures.

The identified ~E-W trending faults cut marker B and younger horizons (younger than 5.5 kyr), and are truncated by an abrasion surface (Fig. 3a) beneath the inner shelf that, according to Milia *et al*. (2000), formed ~3.9-4.0 kyr.

Considering the given chronostratigraphic attribution, the E-W striking faults of the shelf were lastly active at the end of Epoch 3, when the largest volcanic unrest and ground deformation occurred in the Campi Flegrei caldera (Isaia *et al*., 2009; Smith *et al*., 2011; Marturano *et al*., 2018; Isaia *et al*., 2019; Vitale *et al*., 2019).

Moreover, the thickening of marker B from ~1 m on the shelf edge, to ~3 m beneath the shelf west of Pozzuoli harbour suggests that some of these faults were active previously or during deposition of unit B, creating bathymetric lows which were filled by marine-volcanoclastic deposits.

A second fault array (set 2), characterised by NNE-SSW trending near-vertical normal faults, affects the slope south of the central part of the shelf break. Compared to fault set 1, the southern array hosts a more densely spaced network of faults, with a throw ranging from metres to tens of metres (Figs. 4 a and 4b). Thus, their average throw is larger than that of the set 1 faults.

The NNE-SSW faults cut marker B, the abrasion surface, and younger reflectors (Figs. 4a and 4b). Indeed, in the western part of the slope, some set 2 faults cut the 1538 C.E. Monte Nuovo tephra and the sea-floor as well, as the bathymetric expression suggests (Figs. 3b and 4b).

Moreover, in the western part of the bay, we detect the presence of a ~N-S trending east-dipping normal fault system. These faults probably control the morpho-bathymetric alignment of the Epitaffio Valley (EV in Fig. 2). As visible in Fig. 3a, this fault shows small displacement, in the range of tens of centimetres with a cumulative throw of ~1 m.

5. Discussions and conclusive remarks

Our reconstruction of two fault domains with different orientation beneath the submerged part of the Campi Flegrei caldera resurgent dome represents an advancement compared with previous structural maps of the area, which were based on bathymetric data and seismic profiles interpretation (Colantoni *et al.*, 1972; Milia *et al.*, 2000; Sacchi *et al.*, 2014; Di Napoli *et al.*, 2016), earthquakes epicentral location (Di Vito *et al.*, 1999; Orsi *et al.*, 1999), and potential fields methods (Capuano *et al.*, 2013). Specifically, our results suggest that the faults identified using gravity data (Florio *et al.*, 1999; Capuano *et al.*, 2013) represent buried regional structures and do not propagate in the shallow caldera infill.

Moreover, the analysis of a dense network of high-resolution profiles allows us to exclude the existence of a major S-SW dipping normal fault located at the shelf break, as inferred by Capuano *et al.* (2013) and Di Napoli *et al.* (2016). As shown by Sacchi *et al.* (2014), the shelf break is characterised by a prograding wedge genetically related to the abrasion surface (Figs. 2a and 3a). Only in its central part, a slope-recession process has eroded the sedimentary wedge and the abrasion surface, and is probably caused by the activation of NNE-trending faults (Fig. 2a). This morphological observation supports the contention that fault set 2 is younger than fault set 1 beneath the shelf.

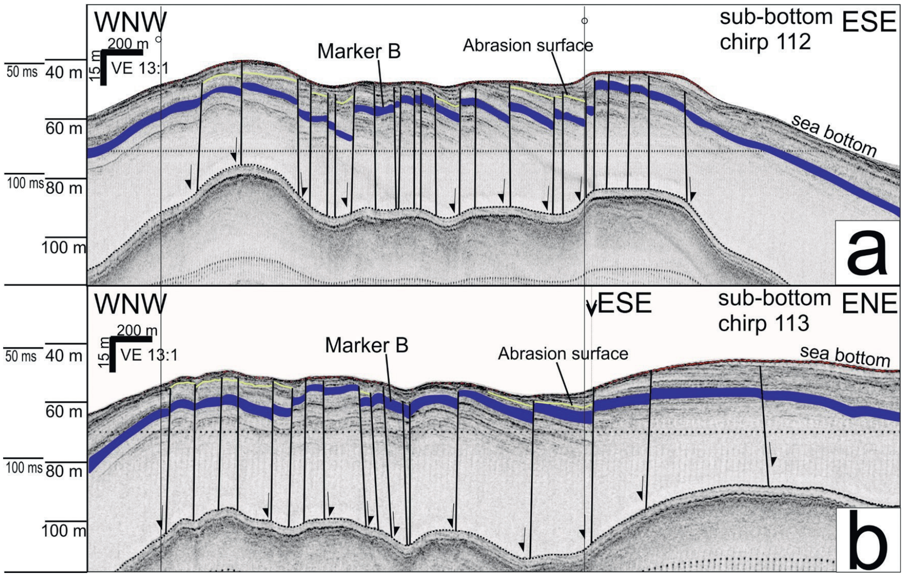

Fig. 4 - a) and b) ~E-W trending sub-bottom chirp profiles showing the dense array of fault set 2 (NNE oriented) displacing marker B up to 15 m and cutting the ~4.0 kyr abrasion surface. Note the consistency of fault displacement along the two parallel profiles, ~260 m apart. Black dotted line: multiple reflection.

Our results partly confirm the reconstruction of Colantoni *et al.* (1972), who identified two fault domains similar to the ones presented here. These authors described an E-W trend similar to our fault set 1 under the shelf, and an NNW-SSE trend underneath the slope, which is more diffuse with respect to our fault set 2. Differently from Colantoni *et al.* (1972), we found that faults of set 2 strike NNE-SSW and are concentrated in a limited area in the central part of the slope. These faults do not seem to continue north of the shelf break, which is dominated by E-W trending faults (Figs. 3b, 4a, and 4b). Regarding the fault system on the western end of the bay, our seismic profiles analysis supports the hypothesis that their activity strongly controls the bathymetric trend (Sacchi *et al.*, 2014; Steinmann *et al.*, 2016). In the context of the recent post-caldera dome resurgence, the E-W and NNE-SSW faults can be related to the broad, regional strain field (e.g. Vitale and Isaia, 2014) and to local volcano-tectonic processes, respectively. In particular, orientation and extension axis of fault set 1 are consistent with the youngest fractures and faults mapped in the on-land part of the dome by Vitale and Isaia (2014) and Vitale *et al.* (2019).

The observation that the western part of the set 2 array cuts younger horizons, including the Monte Nuovo tephra (1538 C.E.), matches the evidence of recent fault activity offshore Monte Nuovo during the last eruption at Campi Flegrei caldera (Di Napoli *et al.*, 2016).

The information provided in this work contributes to the understanding of the geometry and age of volcano-tectonic structures related to the post-caldera evolution. These are critical information to model future unrest and eruptive scenarios and thus to mitigate the seismic and volcanic hazard in such a highly populated area (e.g. Bevilacqua *et al.*, 2015).

Acknowledgements. We thank three anonymous reviewers for the constructive comments that improved this manuscript. This work has been developed in the framework of Jacopo Natale Master's thesis at the University of Naples Federico II. We thank Salvatore Passaro and Giuseppe Vilardo for providing the Digital Elevation Model of Campi Flegrei offshore and onshore sectors, respectively.

REFERENCES

Aiello G., Marsella E. and Di Fiore V.; 2012: *New seismo-stratigraphic and marine magnetic data of the Gulf of Pozzuoli (Napoli Bay, Tyrrhenian Sea, Italy): inferences for the tectonic and magmatic events of the Phlegrean Fields volcanic complex (Campania)*. Mar. Geophys. Res., **33**, 97-125.

Aiello G., Giordano L. and Giordano F.; 2016: *High-resolution seismic stratigraphy of the Gulf of Pozzuoli (Naples Bay) and relationships with submarine volcanic setting of the Phlegrean Fields volcanic complex*. Rend. Lincei, **27**, 775-801.

Albert P.G., Giaccio B., Isaia R., Costa A., Niespolo E.M., Nomade S., Pereira A., Renne P.R., Hinchliffe A., Mark D.F., Brown R.J. and Smith V.C.; 2019: *Evidence for a large-magnitude eruption from Campi Flegrei caldera (Italy) at 29 kyr*. Geol., 47, 595-599, doi: 10.1130/G45805.1.

Bevilacqua A., Isaia R., Neri A., Vitale S., Aspinall W.P., Bisson M., Flandoli F., Baxter P.J., Bertagnini A., Esposti Ongaro T., Iannuzzi E., Pistolesi M. and Rosi M.; 2015: *Quantifying volcanic hazard at Campi Flegrei caldera (Italy) with uncertainty assessment: 1. Vent opening maps*. J. Geophys. Res. Solid Earth, **120**, 2309-2329, doi:10.1002/2014JB011775.

Bevilacqua A., Flandoli F., Neri A., Isaia R. and Vitale S.; 2016: *Temporal models for the episodic volcanism of Campi Flegrei caldera (Italy) with uncertainty quantification*. J. Geophys. Res. Solid Earth, **121**, 7821-7845.

Capuano P., Russo G., Civetta L., Orsi G., D'Antonio M. and Moretti R.; 2013: *The active portion of the Campi Flegrei caldera structure imaged by 3-D inversion of gravity data*. Geochem. Geophys. Geosyst., **14**, 4681-4697.

Chiodini G., Vandemeulebrouck J., Caliro S., D'Auria L., De Martino P., Mangiacapra A. and Petrillo Z.; 2015: *Evidence of thermal-driven processes triggering the 2005-2014 unrest at Campi Flegrei Caldera*. Earth Planet. Sci. Lett., **414**, 58-67.

Colantoni P., Del Monte M., Fabbri A., Gallignani P., Selli R. and Tomadin L.; 1972: *Ricerche geologiche nel Golfo di Pozzuoli*. CNR, Quaderni de "La Ricerca Scientifica", **83**, 26-71.

Deino A.L., Orsi G., de Vita S. and Piochi M.; 2004: *The age of the Neapolitan Yellow Tuff caldera-forming eruption (Campi Flegrei Caldera, Italy) assessed by $^{40}Ar/^{39}Ar$ dating method*. J. Volcanol. Geotherm. Res., **133**, 157-170.

Del Gaudio C., Aquino I., Ricciardi G.P., Ricco C. and Scandone R.; 2010: *Unrest episodes at Campi Flegrei: a reconstruction of vertical ground movements during 1905-2009*. J. Volcanol. Geotherm. Res., **195**, 48-56.

Di Napoli R., Aiuppa A., Sulli A., Caliro S., Chiodini G., Acocella V. and Valenza M.; 2016: *Hydrothermal fluid venting in the offshore sector of Campi Flegrei caldera: a geochemical, geophysical, and volcanological study*. Geochem. Geophys. Geosyst., **17**, 4153-4178.

Di Vito M., Lirer L., Mastrolorenzo G. and Rolandi G.; 1987: *The 1538 Monte Nuovo eruption (Campi Flegrei, Italy)*. Bull. Volcanol., **49**, 608-615.

Di Vito M.A., Isaia R., Orsi G., Southon J., de Vita S., D'Antonio M., Pappalardo L. and Piochi M.; 1999: *Volcanism and deformation in the past 12 kyr at the Campi Flegrei Caldera (Italy)*. J. Volcanol. Geotherm. Res., **91**, 221-246.

Di Vito M.A., Acocella V., Aiello G., Barra D., Battaglia M., Carandente A., Del Gaudio C., de Vita S., Ricciardi G.P., Ricco C., Scandone R. and Terrasi F.; 2016: *Magma transfer at Campi Flegrei caldera (Italy) before the 1538 AD eruption*. Sci. Rep., **6**, 32245, doi: 10.1038/srep32245.

Dvorak J.J. and Berrino G.; 1991: *Recent ground movement and seismic activity in Campi Flegrei, southern Italy: episodic growth of a resurgent dome*. J. Geophys. Res. Solid Earth, **96**, 2309-2323.

Dvorak J.J. and Gasparini P.; 1991: *History of earthquakes and vertical ground movement in Campi Flegrei Caldera, southern Italy: comparison of precursory events to the AD 1538 eruption of Monte Nuovo and of activity since 1968*. J. Volcanol. Geotherm. Res., **48**, 77-92.

Florio G., Fedi M., Cella F. and Rapolla A.; 1999: *The Campanian Plain and Phlegrean Fields: structural setting from potential field data*. J. Volcanol. Geotherm. Res., **91**, 361-379.

Galli P., Giaccio B., Messina P., Peronace E., Amato V., Naso G., Nomade S., Pereira A., Piscitelli S., Bellanova J., Billi A., Blamart D., Galderisi A., Giocoli A., Stabile T. and Thil F.; 2017: *Middle to Late Pleistocene activity of the northern Matese fault system (southern Apennines, Italy)*. Tectonophys., **699**, 61-81.

Hernández-Molina F.J., Fernández-Salas L.M., Lobo F., Somoza L., Díaz-del-Río V. and Alveirinho Dias J.M.; 2000: *The infralittoral prograding wedge: a new large-scale progradational sedimentary body in shallow marine environments*. Geo-Mar. Lett., **20**, 109-117.

Isaia R., Marianelli P. and Sbrana A.; 2009: *Caldera unrest prior to intense volcanism in Campi Flegrei (Italy) at 4.0 kyr BP: implications for caldera dynamics and future eruptive scenarios*. Geophys. Res. Lett., **36**, L21303, doi: 10.1029/2009GL040513.

Isaia R., Vitale S., Marturano A., Aiello G., Barra D., Ciarcia S. and Tramparulo F.D.A.; 2019: *High-resolution geological investigations to reconstruct the long-term ground movements in the last 15 kyr at Campi Flegrei Caldera (southern Italy)*. J. Volcanol. Geothem. Res., **385**, 143-158, doi: 10.1016/j.jvolgeores.2019.07.012.

Lirer L., Luongo G. and Scandone R.; 1987: *On the volcanological evolution of Campi Flegrei*. Eos, Trans. Am. Geophys. Union, **68**, 226-234.

Marturano A., Isaia R., Aiello G. and Barra D.; 2018: *Complex dome growth at Campi Flegrei Caldera (Italy) in the last 15 kyr*. J. Geophys. Res. Solid Earth, **123**, 8180-8197.

Milia A.; 1998: *Stratigrafia, strutture deformative e considerazioni sull'origine delle unità deposizionali oloceniche del Golfo di Pozzuoli (Napoli)*. Boll. Soc. Geol. Ital., **117**, 777-787.

Milia A., Torrente M.M. and Giordano F.; 2000: *Active deformation and volcanism offshore Campi Flegrei, Italy: new data from high-resolution seismic reflection profiles*. Mar. Geol., **171**, 61-73.

Morhange C., Marriner N., Laborel J., Todesco M. and Oberlin C.; 2006: *Rapid sea-level movements and noneruptive crustal deformations in the Phlegrean Fields Caldera, Italy*. Geol., **34**, 93-96.

Mosher D.C. and Simpkin P.G.; 1999: *Status and trends of marine high-resolution seismic reflection profiling: data acquisition*. Geosci. Can., **26**, 174-188.

Neri A., Bevilacqua A., Esposti Ongaro T., Isaia R., Aspinall W.P., Bisson M. and Orsucci S.; 2015: *Quantifying volcanic hazard at Campi Flegrei caldera (Italy) with uncertainty assessment: 2. Pyroclastic density current invasion maps*. J. Geophys. Res. Solid Earth, **120**, 2330-2349.

Orsi G., D'Antonio M., de Vita S. and Gallo G.; 1992: *The Neapolitan Yellow Tuff, a large-magnitude trachytic phreatoplinian eruption: eruptive dynamics, magma withdrawal and caldera collapse*. J. Volcanol. Geotherm. Res., **53**, 275-287.

Orsi G., De Vita S. and Di Vito M.; 1996: *The restless, resurgent Campi Flegrei nested Caldera (Italy): constraints on its evolution and configuration*. J. Volcanol. Geotherm. Res, **74**, 179-214.

Orsi G., Civetta L. Del Gaudio C., De Vita S., Di Vito M.A., Isaia R. and Ricco C.; 1999: *Short-term ground deformations and seismicity in the resurgent Campi Flegrei Caldera (Italy): an example of active block-resurgence in a densely populated area*. J. Volcanol. Geotherm. Res., **91**, 415-451.

Orsi G., Di Vito M.A. and Isaia R.; 2004: *Volcanic hazard assessment at the restless Campi Flegrei Caldera*. Bull. Volcanol., **66**, 514-530.

Passaro S., Barra M., Saggiomo R., Di Giacomo S., Leotta A., Uhlen H. and Mazzola S.; 2013: *Multi-resolution morpho-bathymetric survey results at the Pozzuoli-Baia underwater archaeological site (Naples, Italy)*. J. Archaeolog. Sci., **40**, 1268-1278.

Pescatore T., Diplomatico G., Senatore M., Tramutoli M. and Mirabile L.; 1984: *Contributi allo studio del Golfo di Pozzuoli: aspetti stratigrafici e strutturali*. Mem. Soc. Geol. Ital., **27**, 133-149.

Rosi M. and Sbrana A.; 1987: *Phlegraean Fields*. CNR, Quaderni de “La Ricerca Scientifica”, **114**, 1-175.

Sacchi M., Pepe F., Corradino M., Insinga D.D., Molisso F. and Lubritto C.; 2014: *The Neapolitan Yellow Tuff caldera offshore the Campi Flegrei: Stratal architecture and kinematic reconstruction during the last 15 ky*. Mar. Geol., **354**, 15-33.

Scarpati C., Cole P. and Perrotta A.; 1993: *The Neapolitan Yellow Tuff - A large volume multiphase eruption from Campi Flegrei, southern Italy*. Bull. Volcanol., **55**, 343-356.

Simpkin P.G. and Davis A.; 1993: *For seismic profiling in very shallow water, a novel receiver*. Sea Technol., **34**, 21-28.

Smith V.C., Isaia R. and Pearce N.J.G.; 2011: *Tephrostratigraphy and glass compositions of post-15 kyr Campi Flegrei eruptions: implications for eruption history and chronostratigraphic markers*. Quat. Sci. Rev., **30**, 3638-3660.

Steinmann L., Spiess V. and Sacchi M.; 2016: *The Campi Flegrei Caldera (Italy): formation and evolution in interplay with sea-level variations since the Campanian Ignimbrite eruption at 39 kyr*. J. Volcanol. Geotherm. Res., **327**, 361-374.

Steinmann L., Spiess V. and Sacchi M.; 2018: *Post-collapse evolution of a coastal caldera system: Insights from a 3D multichannel seismic survey from the Campi Flegrei Caldera (Italy)*. J. Volcanol. Geotherm. Res., **349**, 83-98.

Vilardo G., Ventura G., Bellucci Sessa E. and Terranova C.; 2013: *Morphometry of the Campi Flegrei Caldera (southern Italy)*. J. Maps, **9**, 635-640.

Vitale S. and Ciarcia S.; 2013: *Tectono-stratigraphic and kinematic evolution of the southern Apennines/Calabria-Peloritani Terrane system (Italy)*. Tectonophys., **583**, 164-182.

Vitale S. and Isaia R.; 2014: *Fractures and faults in volcanic rocks (Campi Flegrei, southern Italy): insight into volcano-tectonic processes*. Int. J. Earth Sci., **103**, 801-819.

Vitale S., Isaia R., Ciarcia S., Di Giuseppe M.G., Iannuzzi E., Prinzi E.P. and Troiano A.; 2019: *Seismically induced soft sediment deformation phenomena during the volcano-tectonic activity of Campi Flegrei Caldera (southern Italy) in the last 15 kyr*. Tectonics, **38**, doi: 10.1029/2018TC005267.

Corresponding author: Dipartimento di Scienze della Terra, dell’Ambiente e delle Risorse,
Università degli Studi Federico II
Strada Vicinale Cupa Cintia 21, 80126, Napoli, Italy
Phone: +39 081 2538124; e-mail: jacopo.natale@unina.it