Bulletin of Geophysics and Oceanography Vol. 65, n. 4, pp. 535-556; December 2024
DOI 10.4430/bgo00475

Ground uplift and seismic activity at Campi Flegrei caldera (south Italy) during the unrest episodes: an overview

E. Bellucci Sessa and G. Milano

Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli, Italy

(Received: 12 March 2024; accepted: 27 August 2024; published online: 31 October 2024)

ABSTRACT A wide-ranging overview on the ground uplift and seismic activity during the 1969-1972, 1982-1984, and 2005-ongoing unrest episodes at Campi Flegrei caldera is delivered using data reported in literature and those contained in the OV-INGV databases and surveillance reports. In this study, an attempt to correlate the increase of the ground uplift rate and the occurrence of seismic events with $M \geq 1.5$ is made also by reporting some general features on the ground deformations and seismic activity of the 1969-1972 and 1982-1984 unrest episodes. The original graphs, created to compare the ground uplift with the seismic activity, highlight that the increment of the seismic activity, both in number but especially in magnitude, occurs when in the presence of an increment of the ground uplift rate. This feature appears to be common to both the large uplift episodes (1969-1972, 1982-1984, and 2005-ongoing) and the mini-uplift ones (e.g. 2000). Based on our observations on the occurrence of the seismic events with $M \geq 3.5$, we hypothesise that, following an uplift rate of approximately 5 mm/day for a few days, seismic events with $M \geq 4.5$ may occur. Under such hypothesis, also considering the approximate migration of the epicentres of the seismic events with $M \geq 2.5$ of the ongoing unrest, we believe that a reassessment of the seismic hazard for the area of Campi Flegrei could be useful.

Key words: Campi Flegrei caldera, bradyseismic phenomena, geodetic levelling, GNSS data, seismicity.

1. Introduction

Campi Flegrei is an active volcanic area located west of the city of Napoli (Fig. 1). It consists in a depression approximately 12 km wide that is the result of at least two large eruptions: the Campanian Igninbrite, which occurred approximately 39,000 years ago, and the Neapolitan Yellow Tuff, which occurred approximately 15,000 years ago (Rosi and Sbrana, 1987; Orsi *et al.*, 1996; Vitale and Isaia, 2014). After the Neapolitan Yellow Tuff eruption, the activity of the Campi Flegrei caldera (CFc) was very intense with at least 70 eruptions (e.g. Orsi *et al.*, 2004; Di Vito *et al.*, 2016; Trasatti *et al.*, 2023). The last eruption occurred in 1538 producing the Monte Nuovo tuff scoria cone, preceded by ground uplift and seismic activity (Guidoboni and Ciuccarelli, 2011; Di Vito *et al.*, 2016). The CFc is characterised by the bradyseism phenomenon, which consists in a slow subsidence or uplift ground movement. Ground subsidence characterised the CFc after the Monte Nuovo eruption until the end of 1940s. Since 1950, the CFc has been alternating subsidence and uplift phases. Significant recent unrest episodes occurred in 1950-1952, 1969-1972, and 1982-1984 with uplifts of approximately 0.7, 1.7, and 1.8 m, respectively, in the area of maximum deformation, corresponding to the city of Pozzuoli (Del Gaudio *et al.*, 2010; Chiodini *et al.*, 2016). Documented seismic activity accompanied the last two ground uplift movements (Del Gaudio *et al.*, 2010). The cause of the ground uplift of the 1969-1972 and 1982-1984 unrests has been attributed to intrusions of magmatic masses (e.g. Corrado *et al.*, 1977; Berrino *et al.*, 1984 among the first). A large geothermal system is located beneath the CFc at a depth of approximately 2.5-3.0 km (e.g. Rosi and Sbrana, 1987; Piochi *et al.*, 2014), while the most evident manifestations of the hydrothermal activity are concentrated in the Solfatara-Pisciarelli complex (e.g. Caliro *et al.*, 2007; Chiodini *et al.*, 2012), above an inferred isotherms rise zone (Caliro *et al.*, 2007).

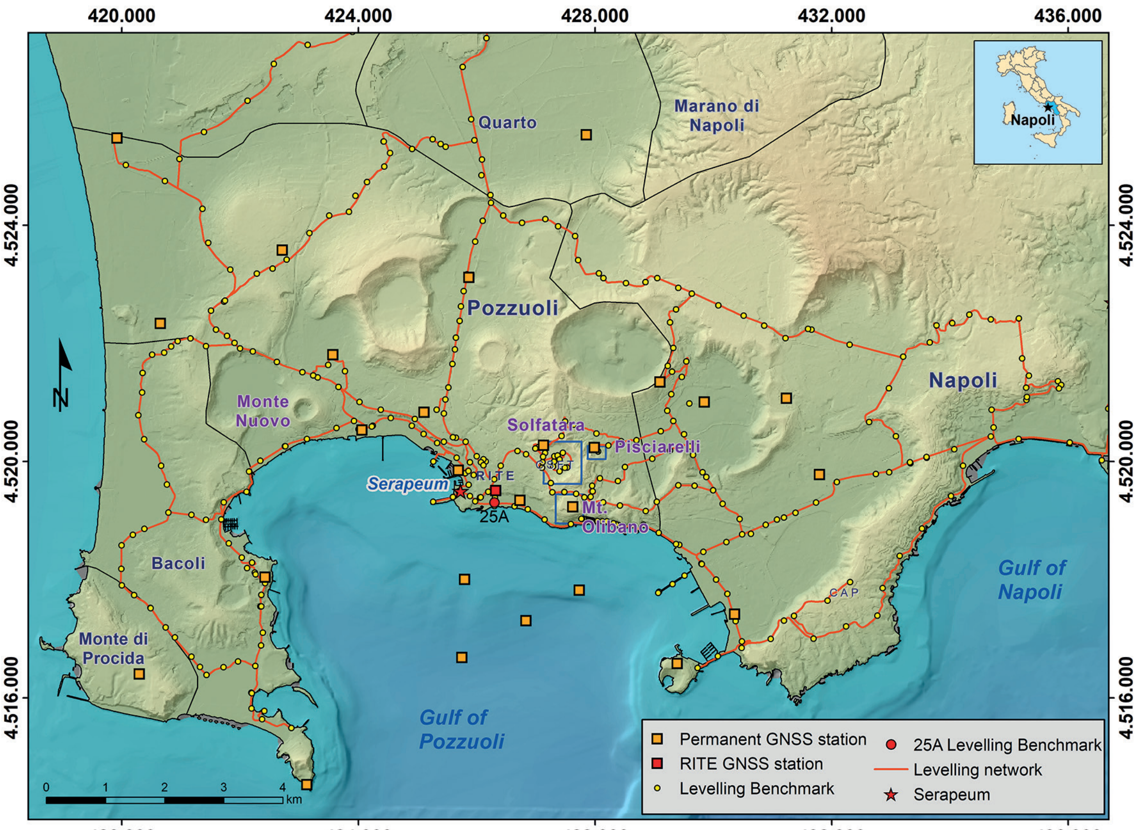

Fig. 1 - Map showing the Campi Flegrei area. The upper right insert reports the location of the area inside the Italian territory. The Digital Terrain Model (DTM) of Campi Flegrei is in UTM WGS84 (Vilardo *et al.*, 2013). The blue squares highlight the Solfatara crater, Pisciarelli area, and Mount Olibano. The Global Navigation Satellite System (GNSS) stations, levelling network, and benchmark are indicated according to the legend on the bottom right.

Since 1985, the CFc has undergone a general subsidence, however in 2005 signs of a new unrest phase were detected. Compared to the previous episodes, deformation is much lower and is accompanied by low seismic activity (M << 1.5). Since the second half of 2017, the seismic activity became more intense and, in September 2023, an M = 4.2 event occurred. Despite the very numerous studies on the CFc, no wide-ranging appraisal between the ground deformation and seismic activity has been carried out on the 1969-1972, 1982-1984, and 2005-ongoing unrest episodes. Generally, seismic activity accompanied ground uplifts whereas no seismic activity occurred during ground subsidence. Ricco *et al.* (2019) investigated the possible relationship between ground deformation and seismic activity in the CFc in the 2015-2018 time range. They proved that major tilt anomalies appear to be related to the rate and energy of volcano-tectonic earthquakes.

Regardless of the causes generating the uplift, generally attributed to the interconnected magmatic and hydrothermal mechanisms, in this study, an overview is provided on the ground uplift and seismic activity during the 1969-1972, 1982-1984, and the 2005-ongoing unrest episodes. We attempt the correlation, if any, between increases of the ground uplift rate and occurrence of seismic events with $M \geq 1.5$. We focus only on the seismic activity with $M \geq 1.5$ as almost all seismic events with this threshold, located on the mainland, are felt by the population and, also, as the OV-INGV (Osservatorio Vesuviano - Istituto Nazionale di Geofisica e Vulcanologia) issues reports of seismic activity for the Italian Civil Protection Department for the above threshold. We utilised the data reported in literature and those contained in the OV-INGV databases and surveillance reports. The first step consisted in the graphical reconstruction of the trend of the vertical ground movements over the last 19 centuries and reporting of some general features on the ground deformations and seismic activity of the 1969-1972 and 1982-1984 unrest episodes. Next, by updating the diagram showing the ground deformation trend for the years 1905-2009 (Del Gaudio *et al.*, 2010), we created original graphs to compare the uplift rate with the seismic activity. Ultimately, differences and/or common aspects between the ongoing and the previous unrest episodes are highlighted and discussed. Investigations considered in this study are up to the end of December 2023.

2. Bradyseism since the 1st century A.D.

The bradyseism trend in the CFc, starting from the 1st century A.D. up to modern times, was possible thanks to the observation of ruins of a monument located in proximity of the harbour of Pozzuoli: the *Macellum*, best known as *Serapeum*. This ancient Roman marketplace is located in the centre of the city of Pozzuoli. Its peculiarity is the presence, at various heights, of lithodome holes on the three still-standing columns, indicating the level reached by the sea in the past. Thanks to the dating of these holes, it was possible to reconstruct the sea level fluctuations due to the subsidence or uplift ground movements in Pozzuoli over time (Di Vito *et al.*, 2016). Since 1905, geodetic techniques have been utilised in the CFc to monitor vertical ground movements. The Italian Military Geographic Institute planned the first levelling network still used today (for details see Del Gaudio *et al.*, 2010), although in the last decades Global Navigation Satellite System (GNSS) data have been utilised (Tammaro *et al.*, 2004; De Martino *et al.*, 2014; Carbonari *et al.*, 2023).

The general bradyseism trend, from the year 34 A.D. to the present day, is shown in Fig. 2. This figure was obtained by utilising the data reported in supplementary material of Di Vito *et al.* (2016) for the period from 34 A.D. to 1900. Starting from 1905, we utilised data reported in the supplementary material of Del Gaudio *et al.* (2010) and, since 2000, the GNSS data (De Martino *et al.*, 2014; Carbonari *et al.*, 2023). Due to the double acquisition of the geodetic data between 2000 and 2009, we homogenised and integrated geodetic levelling and GNSS data to obtain a complete time series. The RITE GNSS station is located 202 m away from the 25A benchmark (Fig. 1). To create continuity with benchmark 25A, the difference in average altitude in the period with double acquisition was calculated in order to bring the altitude of the RITE GNSS station back to that of benchmark 25A. The 25A benchmark features the longest, most uninterrupted data series available. It is also located near the zone of maximum vertical uplift, making it the most important historical benchmark, referred to as 'Datum Point' (Del Gaudio *et al.*, 2009, 2010).

Almost until the second half of the 13th century, a slow subsidence, estimated to be approximately 1.7 m/century, characterised the CFc (Fig. 2A). From approximately 1250, a slow

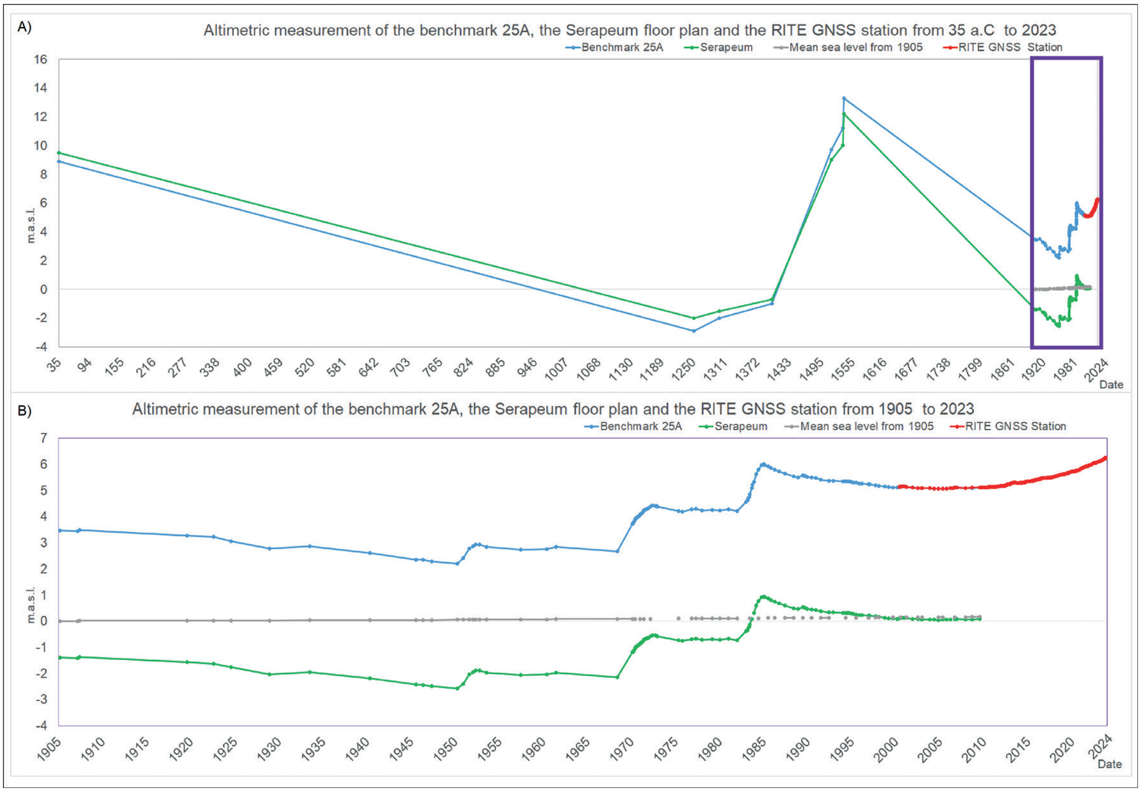

Fig. 2 – A) Reconstruction of the temporal altimetric profile at benchmark 25A and *Serapeum* from 34 A.D. to 2023 [data from: Del Gaudio *et al.* (2010) (1905 to 2009), Di Vito *et al.* (2016) (34 A.D. to 1900), GNSS data from OV-INGV surveillance reports (2000 to 2023)]. The purple area encloses Fig. 2B. B) Altimetric profile at benchmark 25A and *Serapeum* between 1905 and 2023 [data from: Del Gaudio *et al.* (2010) (1905 to 2009), GNSS data from OV-INGV surveillance reports (2000 to 2023)].

reversal of bradyseism, with a rise of approximately 1 cm/year, occurred. Starting almost from the beginning of the 15th century, a significant increase of the ground uplift occurred. Ground uplift was approximately 9 cm/year up to 1535 when an abrupt increment of the uplift rate, of approximately 110 cm/year at *Serapeum* (Di Vito *et al.*, 2016), preceded the Monte Nuovo eruption in 1538. Seismic activity accompanied the sudden ground uplift, with some seismic events being felt in Napoli (Di Vito *et al.*, 2016). Following the eruption, a new subsidence phase, estimated to be only under 4 cm/year, occurred and lasted until the beginning of the 20th century (Fig. 2A). Subsidence continued until 1950 when an unrest phase, which lasted until 1952, occurred (Fig. 2B). In this phase, a ground uplift of approximately 80 cm occurred but the population did not feel any earthquake (Del Gaudio *et al.*, 2010). From 1953, a very slow subsidence continued until the late 1960s.

3. Main features of the previous and ongoing unrests

Over the last decades, the techniques and tools for monitoring volcanic areas have significantly improved and increased. Currently, very dense and detailed monitoring networks run in the CFc for surveillance purposes (Bellucci Sessa *et al.*, 2022). Some of these networks, e.g.

dilatometers, fixed thermal imaging cameras, and continuous gravimetric stations, have been installed starting from 2007. Measurement campaigns are carried out on a monthly, half-yearly, or annual basis to acquire gravimetric data, detailed geochemical data and thermal infrared images utilising Unmanned Aircraft Systems (UAS). All data collected have been published on scientific reports every six months, between 2019 and 2021, and annually since 2022 (Aquino *et al.*, 2021a, 2021b; Bianco and Castellano, 2022a, 2022b, 2023a; 2023b, Bianco *et al.*, 2023). Several of the current methodologies used nowadays, for monitoring purposes and to perform detailed studies on the dynamics of the CFc, did not exist during the 1969-1972 and 1982-1984 unrest episodes. Relatively to the very few methodologies also used in the previous episodes, the different acquisition and/or return methods of the measurements carried out do not enable a direct comparison between data of the same field of study.

3.1. The 1969-1972 unrest

During the first months of 1970, clear evidence of the 80-centimetre ground uplift of the *Serapeum* floor, compared to the 1968 height, was observed. From February 1970 several geodetic levelling surveys were carried out to estimate the precise vertical ground uplift. In particular, 37 geodetic levelling surveys were performed between February 1970 and December 1972 (Corrado *et al.*, 1977). Between April and May 1970, the ground uplift, 2 mm/day, was accompanied by the increment of the seismic activity, geochemical and clinographic phenomena (Liviera Zugiani, 1972; Rampoldi, 1972). This was followed by a decrease in the ground uplift. In October 1970, the ground uplift was of 0.5 mm/day whereas, from April 1971, it was 1 mm/day. Results of the levelling surveys between mid-1968 and October 1971 showed that the uplift occurred at an average rate of approximately 1 mm/day (Liviera Zugiani, 1972), and that the maximum estimated uplift between 1968 and 1972 was of 177 cm in the central area of Pozzuoli. Starting from 1973, slight subsidence again affected the area.

Until 1970, no seismological monitoring network existed at the CFc. Before 1970, the closest seismic station was located in the headquarters of the Institute of Terrestrial Physics of the Napoli University, approximately 12 km away from the city of Pozzuoli. This seismic station had not recorded any seismic activity attributable to the CFc dynamics (Gasparini, 2013). Following the ground uplift of the *Serapeum* floor, the Osservatorio Vesuviano (OV) acquired and installed three three-component seismic stations in early 1970 (Guerra *et al.*, 1972). Successively, the Lithosphere Geophysics Laboratory of the Consiglio Nazionale delle Ricerche (CNR, Milano) installed five three-component seismic stations (Rampoldi, 1972). Guerra *et al.* (1972) reported that between 28 February 1970 and 30 October 1971, the OV seismic network recorded over 2,600 seismic events. Only a portion of the seismic events recorded at one station was detected at the other stations, due to their low intensity. The seismic activity often occurred in swarms. Few events, compared to those recorded, were localised (Fig. 3). Rampoldi (1972) also reported that almost all seismic activity is detected only from a few seismic stations of the CNR network, therefore, suggested the release of low energy by each single event. Few seismic events were recorded at the seismic station located in Napoli, supporting the concept of low energy of the seismic events. From the end of March 1970, the seismic activity became more frequent and on 26 March, the population felt a seismic event. The studies independently carried out by the OV and by the CNR Milano highlighted that the seismic activity was mainly localised in two areas: in the Gulf of Pozzuoli, close to the already-known structural lineaments, ~NW-SE oriented, and in proximity of the Solfatara area (Fig. 3). The depth of the events ranged from a few hundred metres up to 5 km.

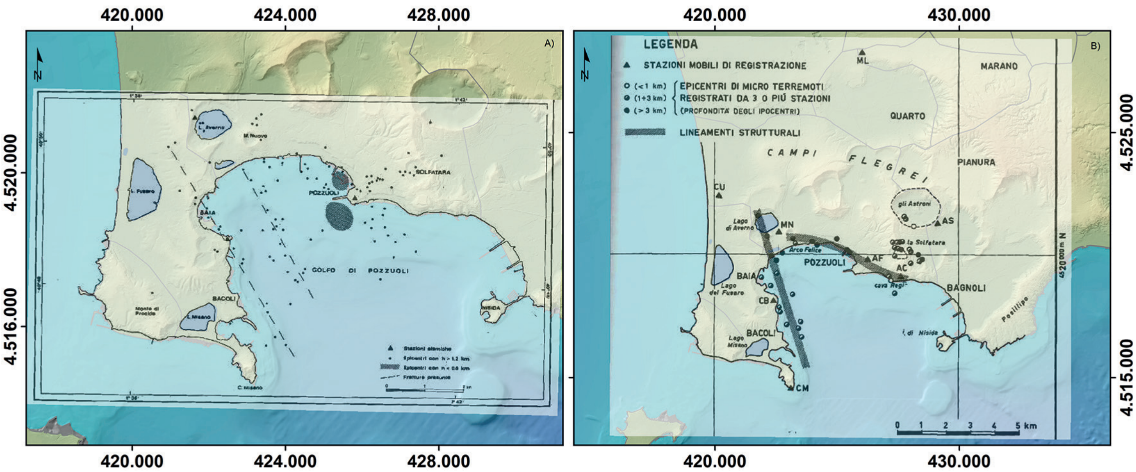

Fig. 3 - Spatial distribution of the located seismicity, which occurred during the 1969-1972 unrest [redraw after: A) Guerra *et al.* (1972) and B) Rampoldi (1972)]. The original figures were scanned and georeferenced in UTM WGS84 to make them compatible with the detailed cartographic bases used in this study. Legend Fig. 3A: triangles = seismic stations; dots = epicentres with h > 1.2 km; dashed area = epicentres with h < 0.5; dashed line = hypothesise fault. Legend Fig. 3B: triangles = temporary seismic stations; dots = epicentres of micro earthquakes acquired from three or more stations (depth of the hypocentres: empty dot < 1 km; half-full 1-3 km; full dot > 3 km); line = structural line.

Few pieces of geochemical information are available for the 1969-1972 unrest: only an increment of the geochemical and clinographic phenomena was reported concurrently with the increase in the ground uplift rate (Liviera Zugiani, 1972; Rampoldi, 1972). Marine gravimetric survey was performed in 1970. To obtain information on land, an extrapolation of the acquired data in the sea was performed (Calligaris *et al.*, 1972). The results of this survey showed a marked negative anomaly in the centre of the caldera, that slightly shifted towards east of the harbour of Pozzuoli. These results were confirmed by aeromagnetic data (Scarascia, 1972). Thermal photos were taken during the 1969-1972 unrest on the walls of the Solfatara and a flight was made with a thermal imaging camera. Data of two radiance measurement campaigns (April 1970 and January 1971) and those acquired by the aircraft showed a general increase in the radiance inside the Solfatara (Tonelli, 1972).

3.2. The 1982-1984 unrest

In 1982, a new unrest phase begun. Following the continuous ground uplift, which started in the summer of 1982, the CFc monitoring system was improved through the increase of geodetic surveys, geochemical measurements, and the installation of additional seismic stations. Between January 1983 and December 1985, 15 geodetic levelling surveys were performed quarterly along the various levelling paths (Fig. 1), whereas they were performed monthly between March and June 1983. These geodetic surveys enabled well estimating the vertical ground movements of the entire CFc area. The ground uplift was not constant. Between January 1982 and April 1983, the ground uplift was approximately 40 cm, between April and July 20 cm, and in the July-October period it was 23 cm. In summary, the 1982-1984 unrest had an average uplift rate of approximately 2 mm/day, with peaks of 4-5 mm/day in some periods (Berrino *et al.*, 1984), with maximum estimated ground uplift being 180 cm in the central area of Pozzuoli.

Seismic activity accompanied the ground uplift (Fig. 4A). Remarkable increase began in the spring of 1983 and, on 15 May, an M = 3.4 event in the Solfatara area occurred. Seismic activity reached very high daily frequency with peaks in October 1983 and April 1984, along with the occurrence of $M > 3.0$ events. Particularly relevant are four events, which occurred in December with $M > 3.0$ ($M_{MAX} = 3.8$), localised between Pozzuoli and Solfatara, and a seismic swarm, which occurred in April 1984 with approximately 600 events in six hours (Fig. 4B). The OV with 22 seismic stations, including the AGIP (Italian Petrol Agency) seismic stations, performed the seismic monitoring of the CFc. From mid-January to April 1984, 12 three-component digital seismic stations, installed by the University of Wisconsin (Madison), in the framework of a scientific cooperation with the OV, also operated in the area [for the location of all the seismic stations installed see Fig. 3 in Del Pezzo *et al.* (1987)]. For more information on the seismic activity between 1982 and 1984, see Scarpa *et al.* (2022).

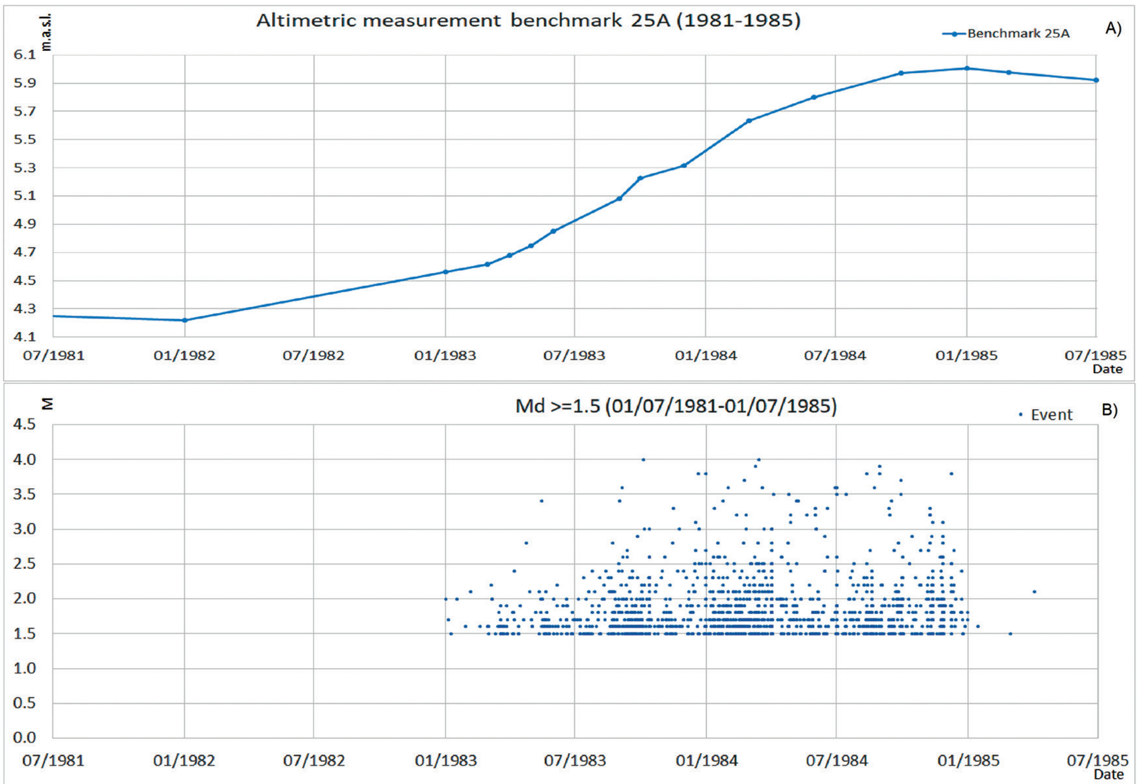

Fig. 4 - A) Altimetric profile at benchmark 25A between July 1981 and July 1985. B) Seismic activity with $M \geq 1.5$, which occurred in the same time period. The stars represent the $M = 4.0$ events.

The 1982-1984 seismic activity is summarised here following. More than 16,000 earthquakes occurred in the CFc with local magnitude ranging between 0.1 and 4.0 (e.g. Iannaccone *et al.*, 2001). This seismic activity was characterised by a prevalence of low energy events (being more than 90% of them with magnitude less than 2.0, and often with swarm activity) constituted by hundreds of events. Almost all seismic activity was located between the city of Pozzuoli and the Solfatara (where the maximum vertical displacement was observed), and in the Gulf of Pozzuoli, close to the already-known structural lineaments [Fig. 5; data from the OV-INGV catalogue (https://terremoti.ov.ingv.it/gossip/flegrei)]. Seismicity nucleated at very shallow depth in the upper 5 km (e.g. Aster *et al.*, 1992; Orsi *et al.*, 1999) and the two strongest events (with $M = 4$, on

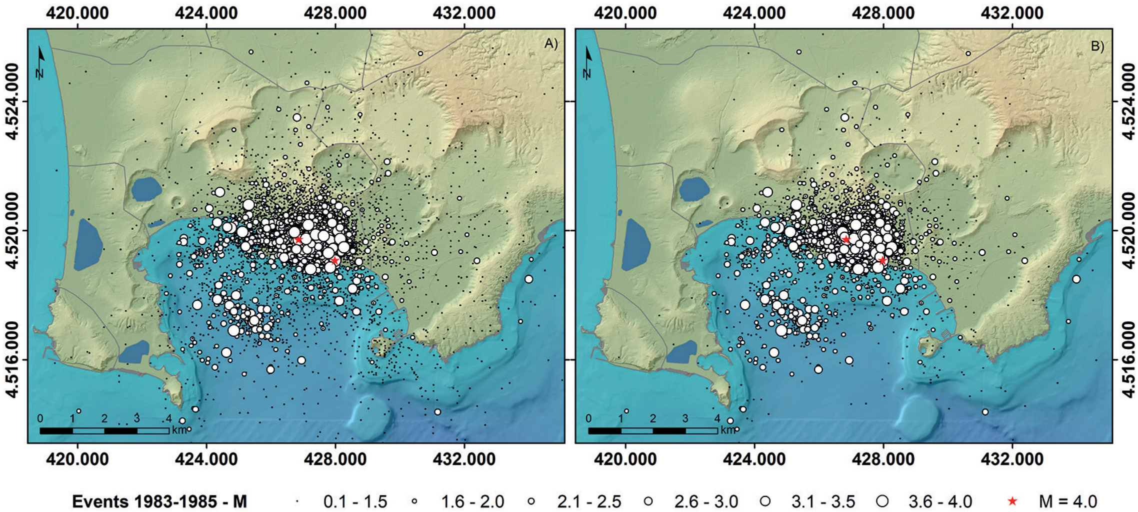

Fig. 5 - Spatial distribution of the 1982-1985 seismicity [data from the OV-INGV catalogue (https://terremoti.ov.ingv.it/gossip/flegrei)]: A) all located seismic events; B) seismic events with $M \geq 1.5$. Circles are proportional to the magnitude of the events (see legend at the bottom). The red stars represent the epicentres of the two M = 4 events.

4 October 1983, and 14 March 1984) are located SE of Mount Olibano and in the Solfatara area (for their location see Fig. 5). The depth of these two events was approximately 2.3 km.

Data on the Solfatara fumaroles have been collected since 1979 (Cioni *et al.*, 1984). During the 1982-1984 period, fumarolic activity strongly increased and chemical changes were detected (e.g. Cioni *et al.*, 1984; Tedesco and Sabroux, 1987; Tedesco *et al.*, 1988). The analyses of the fumarolic fluids collected between October 1983 and February 1984 indicate that they are emitted from a stream reservoir, whose temperature is close to that of the maximum enthalpy of saturated stream (Cioni *et al.*, 1984), located at a depth of approximately 300 m (Tedesco and Sabroux, 1987).

Since 1981, several gravimetric campaigns were carried out. Between January 1983 and July 1984, relevant gravity changes were observed at three stations located close to the centre of Pozzuoli. These changes were attributed to a free-air effect to which a small Bouguer effect must be added (Berrino *et al.*, 1984). The gravimetric stations located along the caldera rim generally showed smaller cumulative changes, but above measurement uncertainty. The most significant gravity changes occurred in the area where the *Serapeum* is located (Bonafede and Mazzanti, 1998).

3.3. The 2005-ongoing unrest

Starting from January 1985 and until 2005, the CFc was affected by slow subsidence that produced 1 m lowering from the altimetric height reached in December 1984 (Fig. 2B). During this subsidence, at least three mini-uplift episodes occurred (Petrazzuoli *et al.*, 2001). The 1989 (3 April), 1994 (24-25 August), and 2000 (8 August) minor uplift episodes were characterised by small ground uplifts, with a max range of 3–11 cm (Gaeta *et al.*, 2003), and were accompanied by low energy seismic activity (3 April 1989 with M_{MAX} = 2.2; 24-25 August 1994 with M_{MAX} = 0.9; 8 August 2000 with M_{MAX} = 2.2).

Since 2005, a new reversal of bradyseism has occurred (see Figs. 2B and 6A). This new ground uplift started in November 2004 and continued to December 2006, producing 4 cm of uplift. As in previous mini-uplift episodes, the variation of the ground uplift rate was accompanied by swarms of micro-earthquakes ($M \leq 1.4$), which, more specifically, occurred in October 2005 ($M_{MAX} = 1.1$), October 2006 ($M_{MAX} = 0.8$), and December 2006 ($M_{MAX} = 1.4$) (Saccorotti *et al.*, 2007) (Fig. 6). Until 2012, most of the seismic activity occurred in low magnitude swarms, i.e. $M < 1.5$ (Bellucci Sessa *et al.*, 2021). These observations, together with the other monitoring ones, led the Italian National Commission for the Forecasting and Prevention of Major Risks and Civil Protection Department to shift the alert status for the CFc from green to yellow. The yellow alert status involves the strengthening of monitoring networks in order to improve observations and increase communications from monthly to weekly. Until the end of 2016, further seismic swarms, generally composed of a few dozen events ($M_{MAX} << 1.8$), also occurred [see Table 1, Figs. 6 and 7; data from the OV-INGV catalogue (https://terremoti.ov.ingv.it/gossip/flegrei)]. The most energetic swarm ($M_{MAX} = 2.5$) occurred in October 2015 (Table 1). Almost all these seismic swarms occurred following a quick increase in the ground uplift rate (Figs. 6 and 7), as also highlighted in Bevilacqua *et al.* (2022).

The variation of the ground uplift rate since the second half of 2017, estimated in 0.7 cm/month, is evident as is the increment of the seismic activity with $M \geq 1.5$ since 2018 (Fig. 6), often characterised by swarm activity (Table 1). Between January 2016 and December 2017, the ground uplift was approximately 20 cm, 13 of which occurred since January 2017. Only the

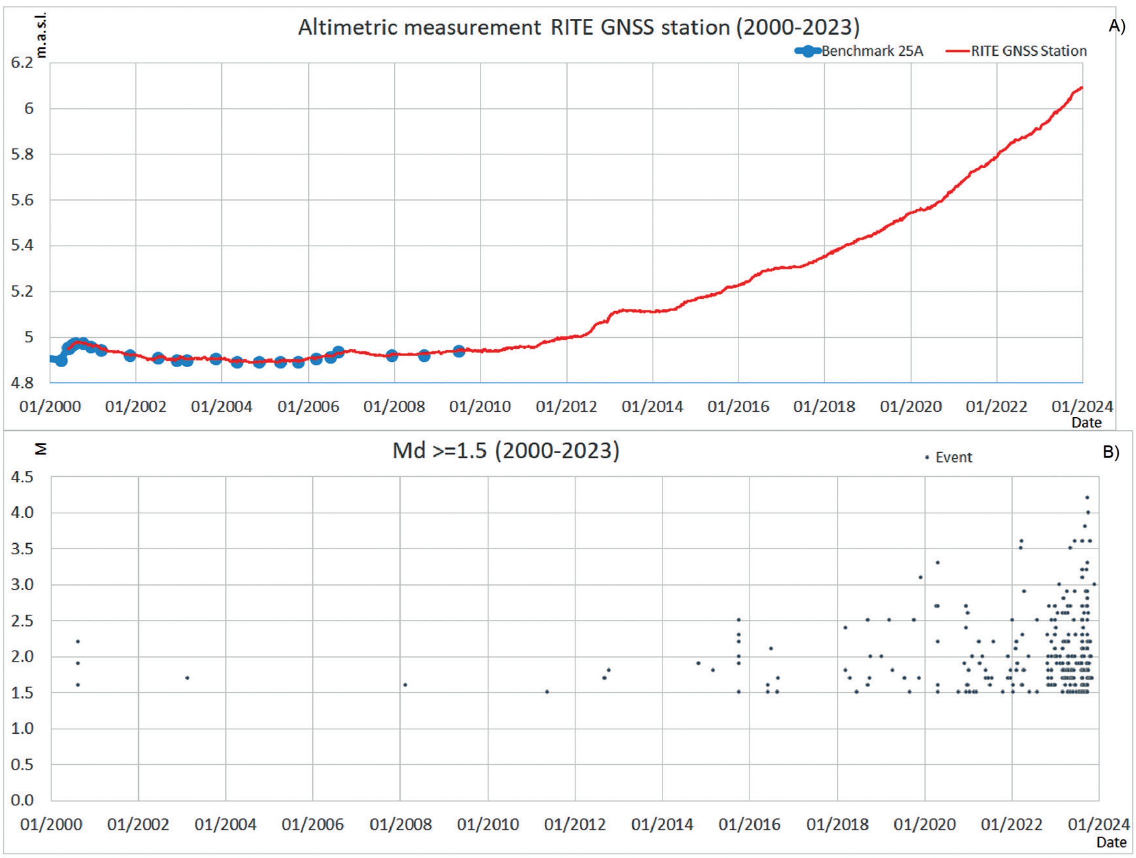

Fig. 6 – A) Altimetric profile at the RITE GNSS station between January 2000 and December 2023 (red line). The blue dots represent the altimetric profile obtained from the geodetic levelling surveys at benchmark 25A until 2009. B) Seismic activity with $M \geq 1.5$ between January 2000 and December 2023.

Table 1 - The CF swarms detected by the geographic information system statistical tool from 2000 to 2023 (updated and modified after Bellucci Sessa *et al.*, 2021).

Date	Number of events	Depth	M_{MAX}
05 Oct. 2005	84	2.28	1.1
23 Oct. 2006	16	1.73	0.8
21 Dec. 2006	6	1.16	1.4
05 Jan. 2008	28	1.89	0.7
30 Mar. 2010	141	1.86	1.2
07 Sept. 2012	188	3.07	1.7
31 Mar. 2014	66	2.00	0.7
07 Oct. 2015	35	1.53	2.5
03 July 2016	47	1.78	0.8
29 Aug. 2016	44	1.86	1.7
12 Mar. 2018	42	2.57	2.4
28 Sept. 2018	12	2.31	1.7
12 Oct. 2018	13	1.77	2.0
12 Nov. 2018	20	2.27	1.4
06 Nov. 2019	12	2.33	3.1
26 Apr. 2020	81	2.57	3.3
20 Dec. 2020	8	1.88	2.4
07 Apr. 2021	12	2.25	1.9
31 May 2021	35	1.37	1.8
21 Oct. 2021	19	1.9	1.5
09 Feb. 2022	5	3.26	2.2
16 Mar. 2022	37	2.54	3.5
05 Apr. 2022	13	1.41	2.3
30 July 2022	10	1.80	2.5
30 Nov. 2022	19	2.38	2.5
03 Dec. 2022	20	1.8	1.6
28 Dec. 2022	74	0.43	2.7
29 Dec. 2022	22	2.6	1.4
05 Feb. 2023	4	4.46	3.0
09 Feb. 2023	16	2.85	2.0
02 Mar. 2023	12	2.36	1.5
04 Mar. 2023	38	2.11	2.6
31 Mar. 2023	14	2.27	1.8
15 Apr. 2023	21	2.36	2.7
17 Apr. 2023	7	4.53	2.2
19 Apr. 2023	11	2.41	1.2
26 Apr. 2023	7	2.4	2.3
02 June 2023	26	2.21	2.5
14 June 2023	24	2.65	2.0
15 June 2023	11	2.79	2.9
25 July 2023	20	2.4	1.5
12 Aug. 2023	19	0.9	1.2

Table 1 - continued.

Date	Number of events	Depth	M_{MAX}
15 Aug. 2023	26	2.1	1.3
16 Aug. 2023	14	2.5	1.6
17 Aug. 2023	292	2.6	3.6
21 Aug. 2023	84	2.6	2.4
02 Sept. 2023	14	2.7	1.6
07 Sept. 2023	31	2.5	3.8
22 Sept. 2023	28	2.1	3.2
22 Sept. 2023	86	2.5	2.1
26 Sept. 2023	186	2.8	4.2
27 Sept. 2023	203	1.7	2.1
29 Sept. 2023	41	2.8	2.7
01 Oct. 2023	24	3.8	2.2
01 Oct. 2023	18	2.5	2.9
02 Oct. 2023	76	2.6	4.0
04 Oct. 2023	13	2.5	2.6
12 Oct. 2023	15	0.8	1.7
16 Oct. 2023	21	2.1	3.6
19 Oct. 2023	12	2.5	2.2

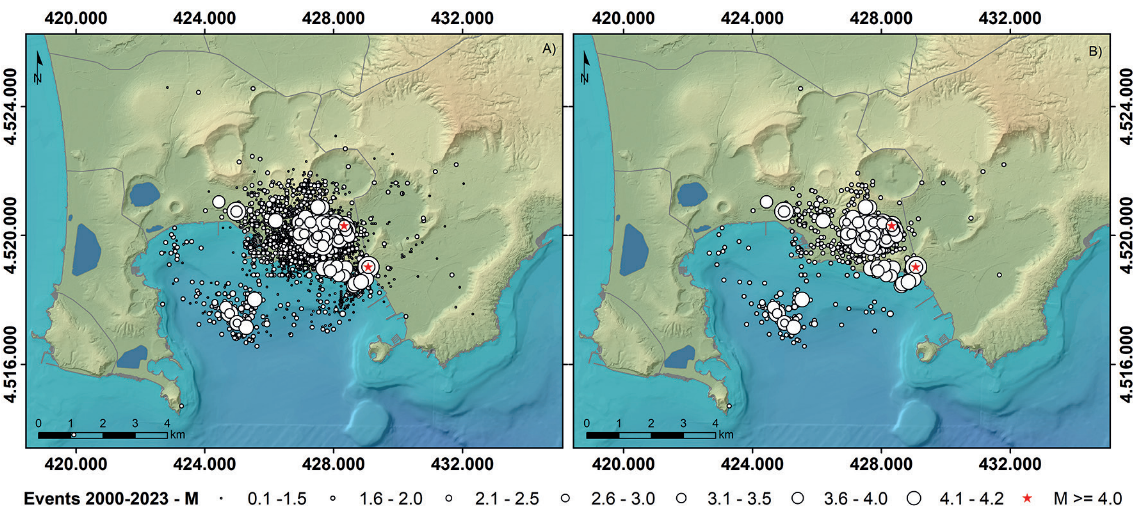

Fig. 7 - Spatial distribution of the seismicity, which occurred between January 2000 and December 2023 [from the OV-INGV catalogue (https://terremoti.ov.ingv.it/gossip/flegrei)]: A) all located seismic events; B) seismic events with $M \geq 1.5$. Circles are proportional to the magnitude of the events (see legend at the bottom). The stars represent the epicentres of the two $M \geq 4$ events.

main features of the ground uplift since 2018 are reported below, being several details already reported in the OV-INGV surveillance bulletins (https://www.ov.ingv.it/index.php/monitoraggio-e-infrastrutture/bollettini-tutti/bollett-mensili-cf). For more information on the seismic activity between 2000 and 2020, see Tramelli *et al.* (2022).

Following the change in the ground uplift rate, since spring 2020 increases of the seismic activity, both in number and in magnitude, occurred. Between September and December 2020, the ground uplift was approximately 10 mm/month in comparison with the 6 mm/month since January. Following the early 2021 further ground uplift rate, increase of the seismic activity occurred and, in the spring of 2022, two events with $M \geq 3.5$ occurred (Fig. 8). Seismic activity significantly increased from early 2023, following a new increase of the ground uplift (15±3 mm/month), also with $M > 3.0$ events. Between 21-23 September, the RITE GNSS station recorded a ground uplift of approximately 10 mm and three days after, on 27 September, an $M = 4.2$ event occurred (for location see Figs. 7 and 9). This event is the most energetic one that occurred in the CFc since the end of the 1982-1984 unrest episode until the end of 2023. Since November 2005, the ground uplift at the RITE GNSS station was approximately 115 cm. After the events with $M = 4.0$ (2 October) and $M = 3.6$ (16 October), seismic activity has undergone a sharp decrease. Between 20 October and 31 December, 270 events ($-1 \leq M \leq 3$) occurred, five of which with magnitude greater than 1.5 (26 October with $M = 2.0$, 26 October with $M = 1.7$, 4 November with 2 events with $M = 1.7$, and 23 November with $M = 3.0$) (https://www.ov.ingv.it/index.php/monitoraggio-e-infrastrutture/bollettini-tutti/bollett-mensili-cf). The most energetic events ($M \geq 2.5$) are almost all located between the city of Pozzuoli and the Solfatara-Pisciarelli area, and only few of them are located in the Gulf of Pozzuoli close to the NW-SE structural lineaments (Figs. 7 and 9). The depth of the $M = 4.2$ and $M = 4.0$ events is 2.8 and 2.6 km, respectively.

Regarding the geochemical data, since 2000 the gas fumarole composition of the Solfatara

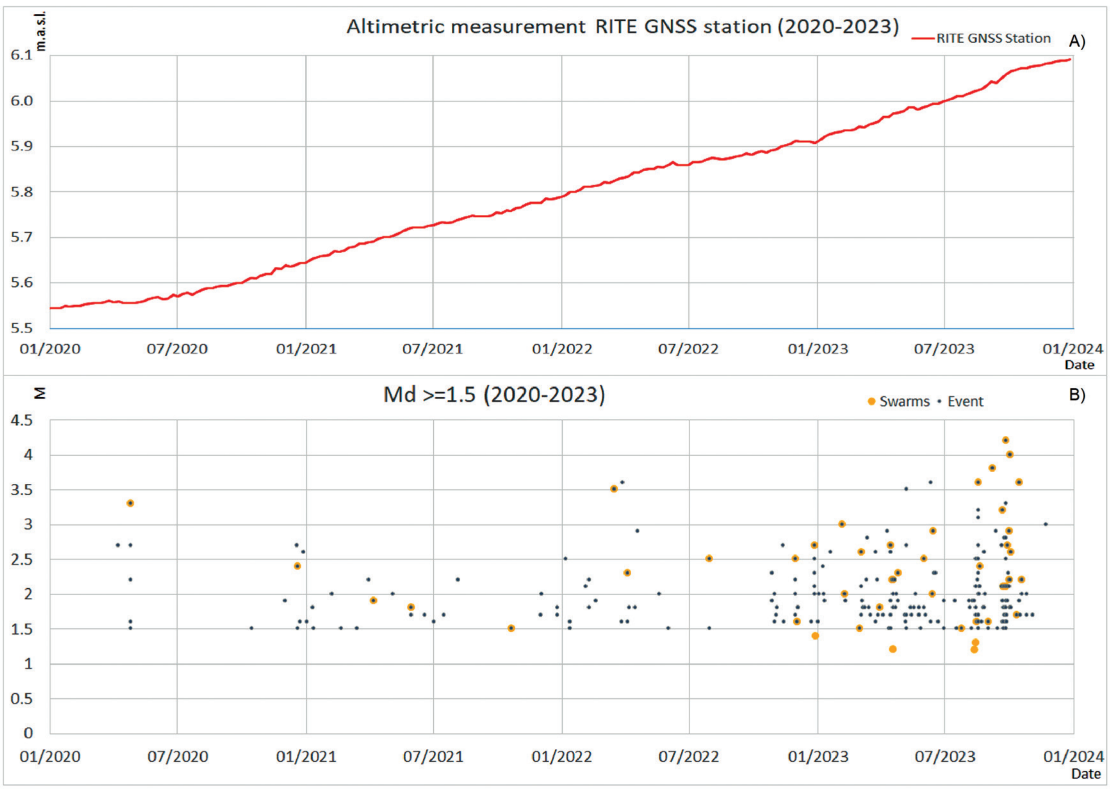

Fig. 8 – A) Altimetric profile at the RITE GNSS station between January 2020 and December 2023. B) Seismic activity with $M \geq 1.5$ occurred in the same time period. The yellow circles represent the seismic swarms, which occurred.

has changed and an increase in carbon dioxide (CO_2) was observed (e.g. Chiodini *et al.*, 2012). Since 2012, a strong increasing degassing activity and variations in the composition of the fluid emissions in the Solfatara-Pisciarelli area were found (Tamburello *et al.*, 2019). The general degassing process increase observed was attributed to a mixture of magmatic-derived fluids, to which a meteorologically derived hydrothermal component is added (e.g. Caliro *et al.*, 2007; Chiodini *et al.*, 2012). Evidence of movements of fluid was also reported (Giudicepietro *et al.*, 2021; Petrosino and De Siena, 2021).

No statistically significant gravimetric variations were observed between 2000 to 2017 (Berrino and Ricciardi, 2020). Since 2018, gravity changes occurred, showing alternating decreases (March-October 2018) and increases (October 2018 - February 2019). After the 2019 measurement campaign, statistically significant gravity variations were recorded on two stations located on the coastal strip east of Pozzuoli (Berrino and Ricciardi, 2020). Following the February 2022 campaign, minimal gravity variations were recorded along the coast east of Pozzuoli (Carlino *et. al.*, 2023).

The ground and seafloor deformation pattern since 2000 is characterised by the invariance of the uplift area with the persistence of a bell-shaped geometry. The horizontal displacement shows a radial pattern from the zone of maximum vertical deformation located in the centre of Pozzuoli (De Martino *et al.*, 2021). The tiltmetric network, since 2005, has detected variations in ground uplift that agree with other geodetic networks. Between 2018 and mid-2020, a variation, caused by a local source, was detected in the area of the volcanic dome of Mount Olibano (Falanga *et al.*, 2023). Ultimately, both data from permanent thermal imaging cameras and those from UAS flights have shown no major changes in thermal emissions over time and space since they were in operation (Caputo *et al.*, 2019). By eliminating the effect of seasonality, since 2018 a clear endogenous force has prevailed on the atmospheric factor, which has strongly dominated soil temperature variations (Cusano *et al.*, 2021).

4. Discussion

4.1. Comparison between the 1969-1972 and 1982-1984 episodes

The direct comparison between the 1969-1972 and 1982-1984 episodes can be made only for the ground deformations as these data were acquired by geodetic levelling. On the contrary, the comparison on the seismic activity can be partially carried out due to the very few seismic stations operating and the magnitudes of the located events that are not available for the first unrest. Nevertheless, some considerations can be made.

The 1969-1972 and 1982-1984 unrest episodes produced a similar ground uplift, 1.77 m and 1.80 m, respectively, although they occurred over a different time interval (Fig. 2). The average uplift rate was 1 mm/day and 2 mm/day for the 1969-1972 and 1982-1984 unrests, respectively. The different segment slopes, related to the two episodes in the altimetric profile, well evidence this aspect (Fig. 2B). The seismicity of the two episodes is mainly localised in the area of maximum vertical deformation, which corresponds to the city of Pozzuoli, and in the Gulf of Pozzuoli, close to the ~NW-SE oriented well-known structural lineament (Figs. 3 and 5). The population felt very few events in the first episode whereas numerous events were felt during the second one. The seismicity of the first unrest that was felt occurred in the spring of 1970 when an increase in the ground uplift rate was detected [2 mm/day: Liviera Zugiani (1972)] in comparison with the previous months. Following Del Gaudio *et al.* (2010), the maximum magnitude was M = 2.5 and, probably, the population felt all $M \geq 1.5$ seismic events located on the mainland. Relatively to the 1982-1984 unrest, the seismic activity with $M \geq 1.5$ appears since January 1983 and the most energetic events ($M \geq 2.5$) and several swarm activities, characterised by hundreds of events, occurred following a rapid change of the ground uplift rate compared to the previous time period (Figs. 4 and 5). For example, the events of 4 October 1983 and 14 March 1984, both with $M = 4.0$, occurred when the ground uplift rate increased from ~2.5 to ~4.5 mm/day and from ~1.5 to ~3.5 mm/day, respectively (Figs. 4 and 5).

4.2. Comparison between the ongoing unrest and previous ones.

The comparison between the ongoing unrest and previous ones is more complex due to the different quality of the acquired data. Regarding the ground deformation, as explained in section 2, data between 1905 and 2009 were acquired by geodetic levelling, whereas, since 2000, they were also acquired by GNSS, and, since 2010, only by GNSS. Data integration led to obtain a complete time series. Regarding the seismic activity, during the 1982-1984 unrest, 20 permanent analogic seismic stations, of which only a few were three-component seismic stations, operated. Since 2012, the geophysical networks operating in the CFc for surveillance purposes were updated following the change in the alert level status. The detection of the seismic events significantly increased over the last 15 years compared to that of the 1982-1984 unrest thanks to the installation of digital more performing three-component seismic stations. Nonetheless, a wide-ranging comparison is, however, plausible.

The ongoing unrest shows a different behaviour compared to the previous ones. Although the spatial distribution of the seismicity is roughly similar to that of the two previous episodes (Figs. 3, 5, and 7), and in particular that of 1982-1984, the deformation is much lower and produced a ground uplift of approximately 1.15 m spread over about 18 years. Between December 2022 and January 2023, the ground uplift reached the maximum height of the 1982-1984 episode. Considering the uplift rate trend that significantly varies with time (Fig. 6), the ongoing episode is divided into three phases: between 2005 and 2011, 2012 and mid-2017, and late 2017 and present-day. The first phase is characterised by slow uplift, ~10 cm for the entire phase, and scarce seismicity, apart from swarm activities ($M_{MAX} = 1.4$) between October 2005 and December 2006 reported in Saccorotti *et al.* (2007) (also see Table 1). These swarm activities could mark the beginning of the reversal phase of the bradyseism since they occurred following the change in slope of the curve representing the altimetric profile at the RITE GNSS station (Fig. 6). The ground deformation trend in the second phase appears very articulated. After a quick uplift between mid-2012 and early 2013, accompanied by seismic activity with $M \geq 1.5$ (Fig. 6), no remarkable ground uplift and seismic activity occurred until the end of 2014. The resumption of the uplift, from the end of 2014, was, once again, accompanied by seismic activity (Fig. 6). In this phase, the average uplift was ~29 cm, of which ~10 cm between mid-2012 and 2013, and ~19 cm between the end of 2015 and mid-2017. In the third phase, the ground uplift underwent a significant increase of ~78 cm (~25 cm from 2017 to early 2020; ~29 cm from mid-2020 to mid-2022; and ~16 cm for all 2023). As a consequence, a sensible increment of the seismic activity, both in number and in magnitude, occurred. This is particularly relevant starting from early 2023 when the magnitude of the seismic events (as well as the swarm activity) remarkably increased, until the end of 27 September, when the $M = 4.2$ event occurred (Figs. 6 and 8). The ground uplift of ~10 mm in three days, 21-23 September (www.ov.ingv.it/index.php/monitoraggio-e-infrastrutture/bollettini-tutti/bollett-mensili-cf/anno-2023-1/1431-bollettino-mensile-campi-flegrei-2023-10/file), preceded this event.

Almost all the seismic events with $M \geq 2.5$ of the ongoing episode have occurred since spring 2020 and are predominantly located in Solfatara-Pisciarelli area (Fig. 9), at a depth between 2.5 and 3.0 km. Looking at the seismic activity of the 1982-1984 episode, the $M \geq 2.5$ events were located in the same area (Fig. 9), at depths not exceeding 3 km. Although their magnitude is not available, several events of the 1969-1972 unrest were localised in the Solfatara-Pisciarelli area.

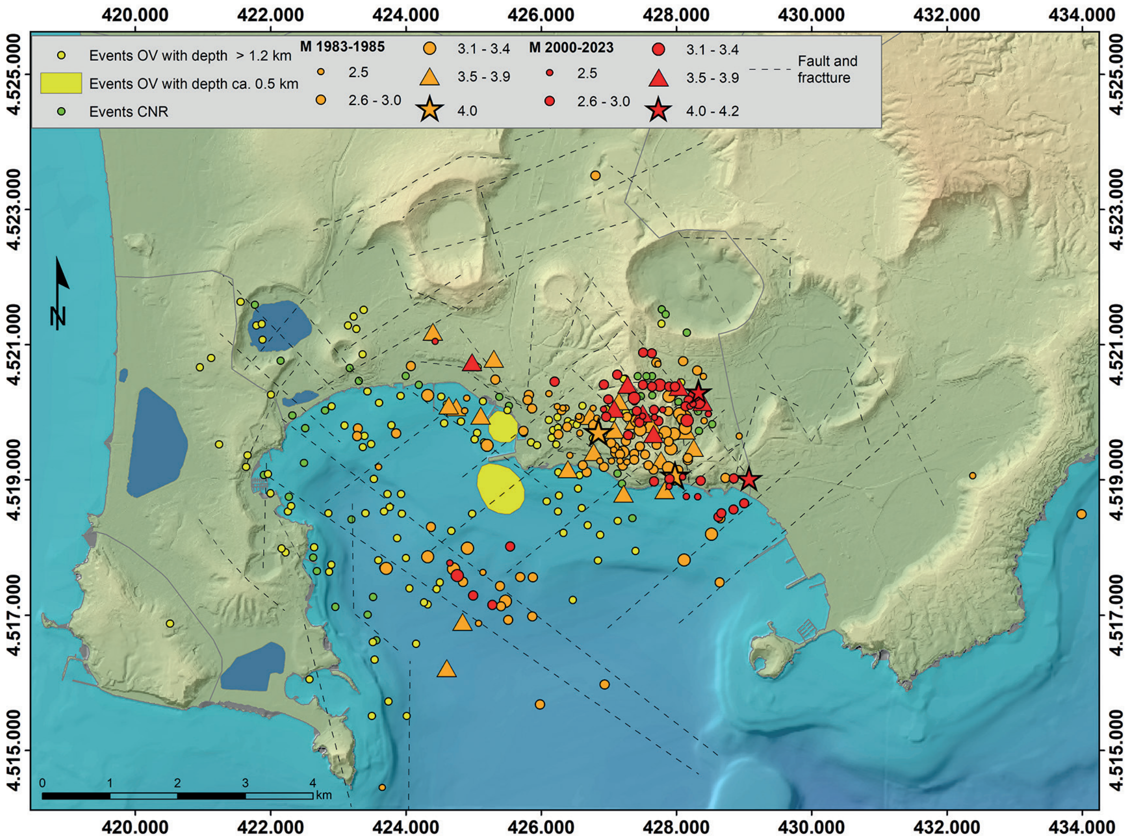

Fig. 9 - Spatial distribution of the 1982-1985 (orange symbols) and of the 2000-2023 (red symbols) seismicity with $M \geq 2.5$ [from the OV-INGV catalogue (https://terremoti.ov.ingv.it/gossip/flegrei)]. The stars are the epicentres of the events with $M \geq 4$ (see legend at the top for all symbols and colours used). The spatial distribution of the located seismicity, accompanying the 1969-1972 unrest, is also reported: yellow dots (Guerra *et al.*, 1972), green dots (Rampoldi, 1972). The yellow areas represent the locations of the seismic events with depths less than 0.5 km (Guerra *et al.*, 1972).

4.3. Considerations on the ongoing unrest and previous ones

The comparisons discussed in the previous two paragraphs show that the increment of the seismic activity occurs when in the presence of an increase in the ground uplift rate compared to the previous time period (Figs. 6 and 8). This aspect would appear to be a common feature to the last two and to the ongoing episodes, although they developed in different time intervals. The seismic activity that accompanied the mini-uplift episodes showed similar characteristics to those accompanying the large unrest episodes. Seismicity accompanying the 2000 mini-uplift was very similar to the one that occurred during the 1969-1972 and 1982-1984 unrest episodes

(Petrazzuoli *et al.*, 2001) but with smaller occurrence and magnitude and it was accompanied by felt seismicity (Gaeta *et al.*, 2003; De Natale *et al.*, 2006), following a rapid change of the ground uplift rate.

The spatial distribution of the seismicity of the two previous and of the ongoing unrests is roughly similar (Figs. 3, 5, and 7). Considering the $M \geq 2.5$ events, which occurred predominantly following a rapid increase of the ground uplift rate (Fig. 8), a migration of the epicentres of the ongoing unrest towards the ENE can be observed when compared with the epicentres of the 1982-1984 unrest (Figs. 5, 7, and 9). Some of those $M \geq 2.5$ events that occurred in 2023 are located beneath the Pisciarelli area, where most of the hydrothermal activity is detected (Tamburello *et al.*, 2019). The gas at the Pisciarelli area, which is located east of the Solfatara crater, is widely emitted from a vent that opened in 2009. Since then, the vent enlarged and the increase of its degassing activity became significant (Chiodini *et al.*, 2015). The $M = 4.0$ event of 2 October 2023 is located beneath the Pisciarelli area (Fig. 7). Further $M \geq 2.5$ events that occurred in 2023 are located along the coastline east of Pozzuoli and a few offshore (Figs. 7 and 9). Along this area, minimal gravity variations were recorded following the 2022 gravimetric campaign (Carlino *et al.*, 2023). The $M = 4.2$ event of 27 September 2023 is located in this zone (Fig. 7). However, the geometric shape of the deformation remains the same of the one previously detected (De Martino *et al.*, 2021), as it is characterised by a radial pattern from the zone of the maximum vertical ground uplift, which corresponds to the centre of Pozzuoli (De Martino *et al.*, 2023a, 2023b).

4.4. Observations on the causes generating the ground uplift

The several studies published in the last years and those in progress all focus on delivering an interpretation on the causes generating the CFc ground uplift. With regards to the 1969-1972 and 1982-1984 unrest episodes, mainly based on the results of ground deformations, seismic activity and gravimetric changes, several authors agree that a magma rising is the main responsible for the ground uplift (Liviera Zugiani, 1972; Corrado *et al.*, 1977; Berrino *et al.*, 1984; Luongo *et al.*, 1989; Civetta *et al.*, 1995; Orsi *et al.*, 1999; Del Gaudio *et al.*, 2005, 2009; Bonafede *et al.*, 2022). The geometric shape of the deformation for these unrests had a circular symmetry around the town of Pozzuoli and decreased towards the margin of the caldera. The contribution of fluid movements and pressure variations of the hydrothermal system was also recently suggested for the 1982-1984 unrest episode (De Siena *et al.*, 2017).

Although several data acquired in the last years enabled performing detailed studies on the dynamics of CFc, the articulated and prolonged ongoing unrest is matter of open debate, as testified by the different interpretations. The quick increase of the ground uplift rate that occurred between mid-2012 and early 2013, also accompanied by strong degassing, has been interpreted as caused by magmatic intrusions in the uppermost crust (D'Auria *et al.*, 2015; Chiodini *et al.*, 2017). Macedonio *et al.* (2014) propose that the ground deformation and seismicity are due to a sill intrusion in a shallow volcanic environment fed by a deeper magma reservoir. In this interpretation, it is not excluded that fluid migration may contribute to the deformation. Both a magma rising and fluid migration are also proposed by Giudicepietro *et al.* (2017). The presence of a magma reservoir, at a depth of 8-9 km beneath the CFc has been proposed by Zollo *et al.* (2008). Moretti *et al.* (2017) hypothesised that the shallow sills intruded and responsible for the 1969-1972 and 1982-1984 episodes have completely cooled and that the ongoing uplift is mostly driven by deeper, CO_2-rich magmatic gas. Based mainly on the geochemical observations between 2010 and 2020, Chiodini *et al.* (2021) highlight the role of overpressure of the hydrothermal system and suggest that the increment of the seismic activity and the very high surface gas emission are due to pressure-temperature increase at the top of a vertical elongated (0.3 -2 km deep) gas front.

Several studies highlighted the role of geochemical signals, which follow or are simultaneous with the geophysical ones (Todesco *et al.*, 2003; Chiodini *et al.*, 2017; Tramelli *et al.*, 2021), to explain the causes generating the ground uplift. The role of the geochemical signals is supported by the strong increasing degassing activity and variations in the composition of the fluid emissions in the Solfatara-Pisciarelli hydrothermal system since 2012 (Tamburello *et al.*, 2019) and by the evidence of fluid movements (Giudicepietro *et al.*, 2021; Petrosino and De Siena, 2021). The physical-chemical perturbation of the hydrothermal system is also taken into account (Buono *et al.*, 2023). Considering that even interpretations based on the magma rising as being responsible for ground uplift often take geochemical data into account (Macedonio *et al.*, 2014; De Siena *et al.*, 2017), increased knowledge of magma-hydrothermal interactions would appear to be a key issue in understanding the CFc dynamics.

5. Conclusive remarks

In this paper, we delivered a wide-ranging overview on the ground uplift and seismic activity during the last two and the ongoing unrest episodes at CFc using published data and that contained in the OV-INGV databases. Based on the comparisons discussed in section 4, the increment in seismic activity, both in number but especially those with $M \geq 2.5$, occurs when there is a rapid increase in the ground uplift rate compared to the previous time period (Figs. 6 and 8). This would appear to be a common feature to the last two and to the ongoing episodes (although they developed in different time intervals) as well as for the mini-uplift episodes such as the one that occurred in 2000. Concerning the ongoing unrest, low magnitude events accompanied the slow uplift observed until 2016 whereas the increase of the ground uplift rate observed in 2017 was followed by an increment of the seismic activity. Since 2020, the increment of the magnitude of the events occurred following the further increase, compared with the previous three years, of the ground uplift rate. Relatively to the 1982-1984 episode, the magnitude of the events increased when a rapid increment of the ground uplift rate occurred. In addition, the felt seismicity of the 1969-1972 unrest occurred following the increase of the ground uplift rate.

The low energy ($M < 1.5$) swarm seismicity of 2005-2006, that could mark the beginning of the ongoing unrest, occurred following the reversal of the ground motion. Relatively to the 1950-1952 unrest, producing a ground uplift of 0.7 m over two years (Fig. 2), no seismic network operated in the area and, therefore, no information between the ground uplift and seismic activity could be obtained. Considering that no felt seismicity occurred and that the seismic activity with magnitude less than 1.5 for both the 1982-1984 and ongoing unrests are, usually, not felt by population, we cannot exclude that the 1950-1952 unrest was also accompanied by low energy seismic events ($M << 1.5$).

The seismicity with $M \geq 2.5$ of the ongoing unrest was predominantly concentrated beneath the Solfatara-Pisciarelli area, the same in which the $M \geq 2.5$ events of the previous unrest were concentrated, at depths not exceeding 3 km. However, a coarse migration of the epicentres of the ongoing unrest towards E-NE, if compared with the epicentres of the 1982-1984 unrest, can be hypothesised. Some of the $M \geq 2.5$ events that occurred in 2023, among which the most energetic ones ($M = 4.2$) that occurred on 27 September 2023, are located along the coastline east of Pozzuoli, where minimal gravity variations were recorded in 2022.

The considerations on the unrest episodes, made in this paper, are limited to the observations on the ground uplift and seismic activity. The ground uplift, in the two years preceding the 1538 eruption, accompanied by felt seismicity, was approximately 19 m in the area where the eruption occurred (Di Vito *et al.*, 2016). The average uplift rate in the same period can be estimated to be approximately 4.0 mm/day at *Serapeum* (Fig. 2A). This value is far higher than the average uplift rate for the 1969-1972 [1 mm/day: Liviera Zugiani (1972)] and for the 1982-1984 [2 mm/day: Berrino *et al.* (1984)] unrests at *Serapeum* (Fig. 2B). Considering the ground uplift rate before the 1538 eruption and taking into account the rates of the previous unrest episodes, with the average present-day ground uplift rate, which can be estimated to be 0.2 mm/day from 2005 to 2023, but 0.4 mm/day between 2020 and 2023 (Figs. 6 and 8), we exclude that an eruption could occur in the next years. However, the seismic events with $M \geq 3.5$, both for the 1982-1984 and for the ongoing unrests, occurred following a rapid increase in the ground uplift rate compared with the previous time period (Figs. 6 and 8). The $M = 4.2$ event of 27 September 2023 occurred after three days in which the ground uplift was approximately 3.5 mm/day whereas it was approximately 0.5 mm/day on average in the previous month. The events of 4 October 1983 and 14 March 1984, both with $M = 4.0$, occurred following a quick increment of the ground uplift, changing from approximately 2.5 to approximately 4.5 mm/day and from approximately 1.5 to approximately 3.5 mm/day, respectively. Based on these observations, we hypothesise that, following an uplift rate of approximately 5 mm/day for a few days, which precedes a period in which the uplift rate was approximately 2 mm/day, seismic events with $M \geq 4.5$ may occur. Under such hypothesis, also considering the coarse migration of the epicentres of the ongoing unrest and the location of the most energetic event that occurred until the end of 2023, we believe that a reassessment of the seismic hazard for the area of Campi Flegrei could be useful.

Acknowledgments. We thank the two anonymous reviewers for their useful comments and suggestions on the manuscript. We also thank the Editor, Antonella Peresan, and express our appreciation for the assistance and suggestions of the Associate Editor, Giuliana Rossi. We are grateful to Carlo Del Gaudio and Ciro Ricco for their courtesy in providing the original levelling data. We also wish to thank Prospero De Martino and Mario Dolce, for their great courtesy in providing the processed RITE station GNSS data, and Eleonora Silvano.

REFERENCES

Aquino I., Augusti V., Avino R., Bagnato E., Bellomo S., Bellucci Sessa E., Belviso P., Benincasa A., Berrino G., Borgstrom S.E., Borriello G., Brandi G., Buongiorno M.F., Buonocunto C. Ciro, Caliro S., Capecchiacci F., Caputo A., Caputo T., Carandente A., Cirillo F., Correale A., Cusano P., D'Alessandro A., D'Alessandro W., D'Errico V., De Cesare W., De Martino P., Di Filippo A., Dolce M., Federico C., Gagliano Candela E., Galluzzo D., Gattuso A.F., Giuffrida G.B., Guardato S., La Pica L., La Rocca A., Liguoro F., Lo Bascio D., Marotta E., Martino C., Minopoli C., Misseri M., Nardone L., Nave R., Orazi M., Pecoraino G., Peluso R., Pinto S., Polcari M., Prano V., Ricciardi G., Ricciolino P., Ricco C., Sansivero F., Santi A., Scaletta C., Scarpato G., Silvestri M., Torello V., Tramelli A. and Vilardo G.; 2021a: *Il Monitoraggio dei Vulcani Campani - Primo semestre 2019*. <http://hdl.handle.net/2122/14589>.

Aquino I., Augusti V., Avino R., Bagnato E., Bellomo S., Bellucci Sessa E., Belviso P., Benincasa A., Berrino G., Borgstrom S.E., Borriello G., Brandi G., Buongiorno M.F., Buonocunto C. Ciro, Caliro S., Capecchiacci F., Caputo A., Caputo T., Carandente A., Cirillo F., Correale A., Cusano P., D'Alessandro A., D'Alessandro W., D'Errico V., De Cesare W., De Martino P., Di Filippo A., Dolce M., Esposito R., Federico C., Gagliano Candela E., Galluzzo D., Gattuso A.F., Giuffrida G.B., Guardato S., La Pica L., La Rocca A., Liguoro F., Lo Bascio D., Marotta E., Martino C., Minopoli C., Misseri M., Nardone L., Nave R., Orazi M., Pecoraino G., Peluso R., Pinto S., Polcari M., Prano V., Ricci T., Ricciardi G., Ricciolino P., Ricco C., Sansivero F., Santi A., Scaletta C., Scarpato G., Silvestri M., Siniscalchi V., Torello V., Tramelli A. and Vilardo G.; 2021b: *Il Monitoraggio dei Vulcani Campani - Secondo semestre 2019.* <http://hdl.handle.net/2122/14820>.

Aster R.C., Meyer R.P., De Natale G., Zollo A., Martini M., Del Pezzo E., Scarpa R. and Iannaccone G.; 1992: *Seismic investigation of the Campi Flegrei: a summary and synthesis of results*. In: Gasparini P., Scarpa R. and Aki K. (eds), Volcanic Seismology, Springer-Verlag, Berlin-Heidelberg, Germany, pp. 462-483, doi: 10.1007/978-3-642-77008-1_28.

Bellucci Sessa E., Castellano M. and Ricciolino P.; 2021: *GIS applications in volcano monitoring: the study of seismic swarms at the Campi Flegrei volcanic complex, Italy*. Adv. Geosci., 52, 131-144, doi: 10.5194/adgeo-52-131-2021.

Bellucci Sessa E., Borriello G. and Cirillo F.; 2022: *Il Monitoraggio nelle aree vulcaniche campane attraverso un "occhio cartografico"*. Miscellanea, Istituto Nazionale di Geofisica e Vulcanologia (INGV), Roma, Italy, <http://hdl.handle.net/2122/16105>.

Berrino G. and Ricciardi G.; 2020: *Repeated absolute gravity measurements on a dense network at Campi Flegrei - a reliable tool for volcano monitoring*. Adv. Geosci., 52, 41-54, doi: 10.5194/adgeo-52-41-2020.

Berrino G., Corrado G., Luongo G. and Toro B.; 1984: *Ground deformations and gravity changes accompanying the 1982 Pozzuoli uplift.* Bull. Volcanol., 47, 187-200, doi: 10.1007/BF01961548.

Bevilacqua A., De Martino P., Giudicepietro F., Ricciolino P., Patra A., Bruce Pitman E., Bursik M., Voight B., Flandoli F., Macedonio G. and Neri A.; 2022: *Data analysis of the unsteadily accelerating GPS and seismic records at Campi Flegrei caldera from 2000 to 2020.* Sci. Rep., 12, 19175, doi: 10.1038/s41598-022-23628-5.

Bianco F. and Castellano M.; 2022a: *Il Monitoraggio dei Vulcani Campani - Primo semestre 2020.* Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Vesuviano (INGV-OV), Napoli, Italy, <http://hdl.handle.net/2122/15424>.

Bianco F. and Castellano M.; 2022b: *Il Monitoraggio dei Vulcani Campani - Secondo semestre 2020.* Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Vesuviano (INGV-OV), Napoli, Italy, <http://hdl.handle.net/2122/15700>.

Bianco F. and Castellano M.; 2023a: *Il Monitoraggio dei Vulcani Campani - Primo semestre 2021.* Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Vesuviano (INGV-OV), Napoli, Italy, <http://hdl.handle.net/2122/16079>.

Bianco F. and Castellano M.; 2023b: *Il Monitoraggio dei Vulcani Campani - Secondo semestre 2021.* Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Vesuviano (INGV-OV), Napoli, Italy, <http://hdl.handle.net/2122/16418>.

Bianco F., Di Vito M.A. and Castellano M.; 2023: *Il Monitoraggio dei Vulcani Campani, 2022.* Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Vesuviano (INGV-OV), Napoli, Italy, <http://hdl.handle.net/2122/16623>.

Bonafede M. and Mazzanti M.; 1998: *Modelling gravity variations consistent with ground deformation in the Campi Flegrei caldera (Italy)*. J. Volcanol. Geotherm. Res., 81, 137-157, doi: 10.1016/S0377-0273(97)00071-1.

Bonafede M., Amoruso A., Crescentini L., Gottsmann J.H., Todesco M. and Trasatti E.; 2022: *Source modelling from ground deformation and gravity changes at the Campi Flegrei caldera, Italy*. In: Campi Flegrei: a restless caldera in a densely populated area, Springer, Berlin-Heidelberg, Germany, pp. 283-309, doi: 10.1007/978-3-642-37060-1_11.

Buono G., Caliro S., Paonita A., Pappalardo L. and Chiodini G.; 2023: *Discriminating carbon dioxide sources during volcanic unrest: the case of Campi Flegrei caldera (Italy)*. Geol., 51, 397-401, doi: 10.1130/G50624.1.

Caliro S., Chiodini G., Moretti R., Avino R., Granieri D., Russo M. and Fiebig J.; 2007: *The origin of the fumaroles of La Solfatara (Campi Flegrei, south Italy)*. Geochim. Cosmoch. Acta, 71, 3040-3055, doi: 10.1016/j.gca.2007.04.007.

Calligaris D., Morelli C. and Pisani M.; 1972: *Rilievo gravimetrico e magnetico*. Quaderni de "La Ricerca Scientifica", 83, 72-81.

Caputo T., Bellucci Sessa E., Silvestri M., Buongiorno M.F., Musacchio M., Sansivero F. and Vilardo G.; 2019: *Surface temperature multiscale monitoring by thermal infrared satellite and ground images at Campi Flegrei Volcanic Area (Italy)*. Remote Sens., 11, 1007, doi: 10.3390/rs11091007.

Carbonari R., Riccardi U., De Martino P., Cecere G. and Di Maio R.; 2023: *Wavelet-like denoising of GNSS data through machine learning. Application to the time series of the Campi Flegrei volcanic area (southern Italy)*. Geomat. Nat. Hazards and Risk, 14, 2187271, doi: 10.1080/19475705.2023.2187271.

Carlino S., Pivetta T. and Ricciari G.; 2023: *CAMPI FLEGREI Monitoraggio Geodetico: Rete Gravimetrica*. In: Bianco F., Di Vito M.A. and Castellano M. (eds), Il Monitoraggio dei Vulcani Campani - 2022, pp. 71-73, <http://hdl.handle.net/2122/16623>.

Chiodini G., Caliro S., De Martino P., Avino R. and Gherardi F.; 2012: *Early signals of new volcanic unrest at Campi Flegrei caldera? Insights from geochemical data and physical simulations*. Geol., 40, 943-946, doi: 10.1130/G33251.1.

Chiodini G., Paonita A., Aiuppa A., Costa A., Caliro S., De Martino P., Acocella V. and Vandemeulebrouck J.; 2016: *Magmas near the critical degassing pressure drive volcanic unrest towards a critical state*. Nat. Commun., 7, 13712, doi: 10.1038/ncomms13712.

Chiodini G., Selva J., Del Pezzo E., Marsan D., De Siena L., D'Auria L., Bianco F., Caliro S., De Martino P., Ricciolino P. and Petrillo Z.; 2017: *Clues on the origin of post-2000 earthquakes at Campi Flegrei caldera (Italy)*. Sci. Rep., 7, doi: 10.1038/s41598-017-04845-9.

Chiodini G., Caliro S., Avino R., Bini G., Giudicepietro F., De Cesare W., Ricciolino P., Aiuppa A., Cardellini C., Petrillo Z., Selva J., Siniscalchi A. and Tripaldi S.; 2021: *Hydrothermal pressure-temperature control on CO2 emissions and seismicity at Campi Flegrei (Italy)*. J. Volcanol. Geotherm. Res., 414, doi: 10.1016/j.jvolgeores.2021.107245.

Cioni R., Corazza E. and Marini L.; 1984: *The Gas/Steam ratio as indicator of heat transfer at the Solfatara Fumaroles, Phlegraean Fields (Italy)*. Bull. Volcanol., 47, 295-302.

Civetta L., Del Gaudio C., de Vita S., Di Vito M., Orsi G., Petrazzuoli S.M., Ricciardi G.P. and Ricco C.; 1995: *Short-term deformational processes in the Campi Flegrei caldera*. In: Atti 14° Convegno annuale del Gruppo Nazionale di Geofisica della Terra Solida, Roma, Italy, pp. 967-971**.**

Corrado G., Guerra I., Lo Bascio A., Luongo G. and Rampoldi R.; 1977: *Inflation and microearthquake activity of Phlegraean Fields, Italy*. Bull. Volcanol., 40, 169-188, doi: 10.1007/BF02596998.

Cusano P., Caputo T., De Lauro E., Falanga M., Petrosino S., Sansivero F. and Vilardo G.; 2021: *Tracking the endogenous dynamics of the Solfatara volcano (Campi Flegrei, Italy): through the analysis of ground thermal image temperatures*. Atmos., 12, 940, doi: 10.3390/atmos12080940.

D'Auria L., Pepe S., Castaldo R., Giudicepietro F., Macedonio G., Ricciolino P., Tizzani P., Casu F., Lanari R., Manzo M., Martini M., Sansosti E. and Zinno I.; 2015: *Magma injection beneath the urban area of Naples: a new mechanism for the 2012-2013 volcanic unrest at Campi Flegrei caldera*. Sci. Rep., 57, S0213, doi: 10.1038/srep13100.

De Martino P., Tammaro U. and Obrizzo F.; 2014: *GPS time series at Campi Flegrei caldera (2000-2013)*. Ann. Geophys., 57, S0213, doi: 104401/ag-6431.

De Martino P., Dolce M., Brandi G., Scarpato G. and Tammaro U.; 2021: *The ground deformation history of the Neapolitan volcanic area (Campi Flegrei Caldera, Somma-Vesuvius volcano, and Ischia Island) from 20 years of continuous GPS observations (2000-2019).* Remote Sens., 13, doi: 10.3390/rs13142725.

De Martino P., Guardato S., Scarpato G., Brandi G. and Dolce M.; 2023a: *CAMPI FLEGREI Monitoraggio Geodetico - Rete GPS (GNSS)*. In: Bianco F., Di Vito M.A. and Castellano M. (eds), Il Monitoraggio dei Vulcani Campani - Secondo semestre 2021, Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Vesuviano (INGV-OV), Napoli, Italy, pp. 54-57, <http://hdl.handle.net/2122/16418>.

De Martino P., Guardato S., Scarpato G., Brandi G. and Dolce M.; 2023b: *CAMPI FLEGREI Monitoraggio Geodetico - Rete GPS (GNSS)*. In: Bianco F., Di Vito M.A. and Castellano M. (eds), Il Monitoraggio dei Vulcani Campani, 2022, Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Vesuviano (INGV-OV), Napoli, Italy, pp. 60-64, <http://hdl.handle.net/2122/16623>.

De Natale G., Troise C., Pingue F., Mastrolorenzo G., Pappalardo L., Battaglia M. and Boschi E.; 2006: *The Campi Flegrei* caldera*: unrest mechanisms and hazard*. In: Troise C., De Natale G. and Kilburn C.R.J. (eds), Mechanisms of active and unrest at large calderas, Geol. Soc., London, UK, Spec. Pub., 269, pp. 25-46, doi: 10.1144/GSL.SP.2006.269.01.03.

De Siena L., Amoruso A., Pezzo E.D., Wakeford Z., Castellano M. and Crescentini L.; 2017: *Space-weighted seismic attenuation mapping of the aseismic source of Campi Flegrei 1983-1984 unrest*. Geophys. Res. Lett., 44, 1740-1748, doi: 10.1002/2017GL072507.

Del Gaudio C., Ricco C., Aquino I., Brandi G., Serio C. and Siniscalchi V. (a cura di); 2005: *Misure di livellazione di precisione e dati tiltmetrici per il controllo delle deformazioni del suolo ai Campi Flegrei*. Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Vesuviano (INGV-OV), Napoli, Italy, Open File Report, 4, 9 pp.

Del Gaudio C., Aquino I., Ricco C. del Serio C.; 2009: *Monitoraggio geodetico dell'area vulcanica napoletana: risultati della livellazione geometrica di precisione eseguita ai Campi Flegrei a settembre 2008*. Quaderni di Geofisica, 66, 1-14.

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*; 2010: J. Volcanol. Geotherm. Res., 195, 48-56, doi: 10.1016/j.jvolgeores.2010.05.014.

Del Pezzo E., De Natale G., Martini M. and Zollo A.; 1987: *Source parameters of microearthquakes at Phlegraean Fields (southern Italy): volcanic area*. Phys. Earth Planet. Inter., 47, 25-42, doi: 10.1016/0031-9201(87)90064-1.

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 (Italy): before the 1538 AD eruption*. Sci. Rep., 6, doi: 10.1038/srep32245.

Falanga M., Aquino I., De Lauro E., Petrosino S. and Ricco C.; 2023: *New insights on ground deformation at Campi Flegrei caldera inferred from kinematics and dynamics investigation of borehole tilt*. Earth Space Sci., 10, doi: 10.1029/2022EA002702.

Gaeta F.S., Peluso F., Arienzo I., Castagnolo D., De Natale G., Milano G., Albanese C. and Mita D.G.; 2003: *A physical appraisal of a new aspect of bradyseism: the miniuplifts*. J. Geophys. Res., 108, 2363, doi: 10.1029/2002JB001913.

Gasparini P.; 2013: *Il bradisismo del 1970.* Ambiente Rischio Comunicazione, 5, 31-35.

Giudicepietro F., Macedonio G. and Martini M.; 2017: *A physical model of sill expansion to explain the dynamics of unrest at calderas with application to Campi Flegrei*. Front. Earth Sci., 5, doi: 10.3389/feart.2017.00054.

Giudicepietro F., Chiodini G., Avino R., Brandi G., Caliro S., De Cesare W., Galluzzo D., Esposito A., La Rocca A., Lo Bascio D., Obrizzo F., Pinto S., Ricci T., Ricciolino P., Siniscalchi A., Tramelli A., Vandemeulebrouck J. and Macedonio G.; 2021: *Tracking episodes of seismicity and gas transport in Campi Flegrei caldera through seismic, geophysical, and geochemical measurements*. Seismol. Soc. Am., 92, 965-975, doi: 10.1785/0220200223.

Guidoboni E. and Ciuccarelli C.; 2011: *The Campi Flegrei caldera: historical revision and new data on seismic crises, bradyseisms, the Monte Nuovo eruption and ensuring earthquakes (twelfth century 1582 AD)*. Bull. Volcanol., 73, 655-677, doi: 10.1007/s00445-010-0430-3.

Guerra I., Lo Bascio A., Luongo G. and Nazzaro A.; 1972: *Rapporto sulla sorveglianza sismica nell'area di Pozzuoli (marzo 1970 - ottobre 1971)*. Quaderni de "La Ricerca Scientifica", 83, 182-186.

Iannaccone G., Alessio G., Borriello G., Cusano P., Petrosino S., Ricciolino P., Talarico G. and Torello V.; 2001: *Characteristics of the seismicity of Vesuvius and Campi Flegrei during the year 2000*. Ann. Geof., 44, 1075-1091, <http://hdl.handle.net/2122/1267>.

Liviera Zugiani B.; 1972: *Controlli altimetrici dei capisaldi nell'area flegrea*. Quaderni de "La Ricerca Scientifica", 83, 263-283.

Luongo C.A., Loyd R.J., Chen F.K. and Peck S.D.; 1989: *Thermal-hydraulic simulation of helium expulsion from a cable-in-conduit conductor*. IEEE Trans. Magn., 25, 1589-1595, doi: 10.1109/20.92602.

Macedonio G., Giudicepietro F., D'Auria L. and Martini M.; 2014: *Sill intrusion as a source mechanism of unrest at volcanic calderas*. J. Geophys. Res.: Solid Earth, 119, 3986-4000, doi: 10.1002/2013JB010868.

Moretti R., De Natale G. and Troise C.; 2017: *A geochemical and geophysical reappraisal to the significance of the recent unrest at Campi Flegrei caldera (southern Italy)*. Geochem., Geophys., Geosyst., 18, 1244-1269, doi: 10.1002/2016GC006569.

Orsi G., De Vita S. and Di Vito M.A.; 1996: *The restless, resurgent Campi Flegrei nested caldera (Italy): constraints on its evolution and configuration*. J. Volcanol. Geotherm. Res., 74, 179-214, doi: 10.1016/S0377-0273(96)00063-7.

Orsi G., Civetta L., Del Gaudio C., de Vita S., Di Vito M.A., Isaia R., Petrazzuoli S.M., Ricciardi G.P. and Ricco C.; 1999: *Short-term 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, doi: 10.1016/S0377-0273(99)00050-5.

Orsi G., Di Vito M.A. and Isaia R.; 2004: *Volcanic hazard assesment at the restless Campi Flegrei caldera*. Bull. Volcanol., 66, 514-530, doi: 10.1007/s00445-003-0336-4.

Petrazzuoli S.M., Del Gaudio C., De Martino P., Di Vito M.A., Isaia R., Orsi G., Ricciardi G.P. and Ricco C.; 2001: *Cyclic Nature of small-scale unrest episodes at the Campi Flegrei caldera*. In: Volcanic hazard assessment and zonation at the resurgent Campi Flegrei caldera and their effects on man and environment, GNV Framework program 2000-2002, I year results, Osservatorio Vesuviano, Napoli, Italy, pp. 128-132.

Petrosino S. and De Siena L.; 2021: *Fluid migrations and volcanic earthquakes from depolarized ambient noise*. Nat. Commun., 12, 6656, doi: 10.1038/s41467-021-26954-w.

Piochi M., Kilburn C., Di Vito M.A., Mormone A., Tramelli A., Troise C. and De Natale G.; 2014: *The volcanic and geothermally active Campi Flegrei caldera: an integrated multidisciplinary image of its buried structure*. Int. J. Earth Sci., 103, 401-421, doi: 10.1007/s00531-013-0972-7.

Rampoldi R.; 1972: *Risultati delle osservazioni sismografiche effettuate dal giugno 1970 al luglio 1971*. Quaderni de "La Ricerca Scientifica", 83, 187-197.

Ricco C., Petrosino S., Aquino I., Del Gaudio C. and Falanga M.; 2019: *Some investigations on a possible relationship between ground deformation and seismic activity at Campi Flegrei and Ischia volcanic areas (southern Italy)*. Geosci., 9, 222, doi: 10.3390/geosciences9050222.

Rosi M. and Sbrana A.; 1987: *The Phlegrean Fields*. Quaderni de “La Ricerca Scientifica”, 114, 9, 175 pp.

Saccorotti G., Petrosino S., Bianco F., Castellano M., Galluzzo D., La Rocca M., Del Pezzo E., Zaccarelli L. and Cusano P.; 2007: *Seismicity associated with the 2004-2006 renewed ground uplift at Campi Flegrei caldera, Italy*. Phys. Earth Planet. Inter., 165, 14-24, doi: 10.1016/j.pepi.2007.07.006.

Scarascia S.; 1972: *Carta aeromagnetica dell’area dei Campi Flegrei - Pozzuoli.* Quaderni de “La Ricerca Scientifica”, 83, 209-217.

Scarpa R., Bianco F., Capuano P., Castellano M., D’Auria L., Di Lieto B. and Romano P.; 2022: *Historic Unrest of the Campi Flegrei caldera, Italy*. In: Scarpa R., Bianco F., Capuano P., Castellano M., D’Auria L., Di Lieto B. and Romano P. (eds), Active volcanoes of the world, Springer Nature, Berlin, Germany, pp. 257-282, doi: 10.1007/978-3-642-37060-1_10.

Tamburello G., Caliro S., Chiodini G., De Martino P., Avino R., Minopoli C., Carandente A., Rouwet D., Aiuppa A., Costa A., Bitetto M., Giudice G., Francofonte V., Ricci T., Sciarra A., Bagnato E. and Capecchiacci F.; 2019: *Escalating CO2 degassing at the Pisciarelli fumarolic system, and implications for the ongoing Campi Flegrei unrest*. J. Volcanol. Geotherm. Res., 384, 151-157, doi: 10.1016/j.jvolgeores.2019.07.005.

Tammaro U., Malaspina S., Serio C., Cecere G., Siniscalchi V., D’Alessandro A., Pinto S., Brandi G., Dolce M. and Russo A.; 2004: *La rete GPS in continuo dell’area vulcanica napoletana: dotazione strumentale, parametri di elaborazione e sviluppi tecnologici*. Istituto Nazionale di Geofisica e Vulcanologia-Osservatorio Vesuviano (INGV-OV), Napoli, Italy, Open File Report, 4, 29 pp.

Tedesco D. and Sabroux J.C.; 1987: *The determination of deep temperatures by means of the CO-CO2-H2-H2O geothermometer: an example using fumaroles in the Campi Flegrei, Italy*. Bull. Volcanol., 49, 381-387, doi: 10.1029/GL015i012p01441.

Tedesco D., Pece R. and Sabroux J.C.; 1988: *No evidence of a new magmatic gas contribution to the Solfatara volcanic gases, during the Bradyseismic crisis at Campi Flegrei (Italy)*. Geophys. Res. Lett., 15, 1441-1444, doi: 10.1029/GL015i012p01441.

Todesco M., Chiodini G. and Macedonio G.; 2003: *Monitoring and modelling hydrothermal fluid emission at La Solfatara (Phlegrean Fields, Italy). An interdisciplinary approach to the study of diffuse degassing*. J. Volcanol. Geotherm. Res., 125, 57-79, doi: 10.1016/S0377-0273(03)00089-1.

Tonelli A.M.; 1972: *Termografie all’infrarosso da stazioni a terra e dall’aereo*. Quaderni de “La Ricerca Scientifica”, 83, 218-230.

Tramelli A., Godano C., Ricciolino P., Giudicepietro F., Caliro S., Orazi M. and Chiodini G.; 2021: *Statistics of seismicity to investigate the Campi Flegrei caldera unrest*. Sci. Rep., 11, doi: 10.1038/s41598-021-86506-6.

Tramelli A., Giudicepietro F., Ricciolino P. and Chiodini G.; 2022: *The seismicity of Campi Flegrei in the contest of an evolving long term unrest*. Sci. Rep., 12, doi: 10.1038/s41598-022-06928-8.

Trasatti E., Magri C., Acocella V., Del Gaudio C., Ricco C. and Di Vito M.A.; 2023: *Magma transfer at Campi Flegrei caldera (Italy): after the 1538 AD eruption*. Geophys. Res. Lett., 50, doi: 10.1029/2022GL102437.

Vilardo G., Ventura G., Bellucci Sessa E. and Terranova C.; 2013: *Morphometry of the Campi Flegrei caldera (southern Italy)*. J. Maps, 9, 635-640, doi: 10.1080/17445647.2013.842508.

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, doi: 10.1007/s00531-013-0979-0.

Zollo A., Maercklin N., Vassallo M., Dello Iacono D., Virieux J. and Gasparini P.; 2008: *Seismic reflections reveal a massive melt layer feeding Campi Flegrei caldera*. Geophys. Res. Lett., 35, doi: 10.1029/2008GL034242.

Corresponding author: Eliana Bellucci Sessa
Istituto Nazionale di Geofisica e Vulcanologia
Sezione Osservatorio Vesuviano
Via Diocleziano 328, 80124 Napoli, Italy
Phone: +39 081 6108216; E-mail: eliana.bellucci@ingv.it