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Key Points:

- In the SE part of Rome city, a shallow confined gas-pressurized aquifer produces frequent hazardous gas blowouts from drillings
- Gas has the highest helium R/Ra of all discharges of the quiescent Colli Albani volcano, indicating a magmatic origin
- In case of volcanic unrest, a harmful phreatic explosion might occur or the emission of hazardous gas might increase

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Hazard From Endogenous Gas Emissions and Phreatic Explosions in Rome City (Italy)

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Abstract A gas blowout during an unauthorized well drilling occurred on June 9, 2020 at the Rome-Ciampino boundary at the periphery of Colli Albani quiescent volcano. This zone hosts a shallow confined gas-pressured aquifer, which recently produced further three gas blowouts. Dangerous atmospheric CO_2 and H_2S concentrations killed some birds, and 12 families were evacuated. The helium isotopic composition indicates that the gas has a magmatic origin. It rises toward the surface along leaky faults, pressurizing the shallow confined aquifer and creating a permanent gas blowout hazard. Colli Albani volcano is characterized by anomalous uplift, release of magmatic gas, and episodic seismic crises. Should a volcanic unrest occur, gas hazard would increase in this densely inhabited zone of Rome city, as the input of magmatic gas into the confined aquifer might create overpressure conditions leading to a harmful phreatic explosion, or increase the emission of hazardous gas through newly created fractures.

Plain Language Summary Rome city is located at the periphery of Colli Albani dormant volcano. Its south-eastern part hosts a shallow confined gas-pressurized aquifer, which can produce a gas blowout, that is, a sudden persistent emission of gas and nebulized water, when reached by drillings. Three blowouts were recorded from 2003 to 2016 and a fourth occurred on June 2020. Air concentration of the emitted carbon dioxide and hydrogen sulfide surpassed their Immediately Dangerous to Life and Health limit. Some birds were killed, and 12 families had to be evacuated. The helium isotopic composition confirms that the gas has a deep origin from the Colli Albani magma reservoir. This part of Rome city is permanently exposed to a gas blowout hazard and might be affected either by a phreatic explosion (i.e., without the direct involvement of magma) or by increasing output of hazardous gas through newly created fractures, in case of volcanic unrest at Colli Albani.

1. Introduction

The southeastern part of Rome city is located at the periphery of Colli Albani, a quiescent alkali-potassic volcano (Figure 1a). Volcanological evidence indicates that the volcano is in a quiescence phase, as the time passed since its last eruption (36 ka) does not overrun the mean duration of the repose periods recorded during its eruptive history (Marra et al., 2016 and references therein).

Lahars have been generated up to Roman times (IV century B.C.) by floodings from lake Albano, which hosts the five most recent craters of the volcano that are aligned on a NW-SE direction (Anzidei et al., 2007). Lahar deposits form the impermeable shallow cover of the Ciampino plain up to Rome (Tavolato formation; Funiciello et al., 2010). On the NW prolongation of the crater alignment, the small Cava dei Selci depression is found (CdS in Figure 1a). Here the impermeable lahar cover has been removed by quarrying excavations, allowing gas rising from depth to freely discharge at the surface. At CdS, dozens of cows and sheep were killed by the gas (mostly CO_2 with ~1 vol. % of H_2S) while watering at a seasonal pond and a man lost his life nearby (Carapezza et al., 2003). Besides convective gas emission from small vents, CdS is also characterized by an anomalous diffuse soil gas release, and many soil CO_2 flux surveys have shown that the most anomalous gas releasing area has an elliptic shape with the major axis NW-SE (Carapezza et al., 2019). In the same NW sector of Colli Albani, a wide anomaly in the P_{CO2} of the ground waters has been recognized; it is associated with $\delta^{13}C_{TDIC}$ and helium R/Ra isotopic values indicating a deep origin of the dissolved gas (Chiodini & Frondini, 2001; Pizzino, 2015).

To the NW of Lake Albano, the Rome gas blowout zone is found (RBZ in Figure 1a), where three gas blowouts from drillings occurred from 2003 to 2016 (Carapezza et al., 2020a). The gas emitted in these accidents

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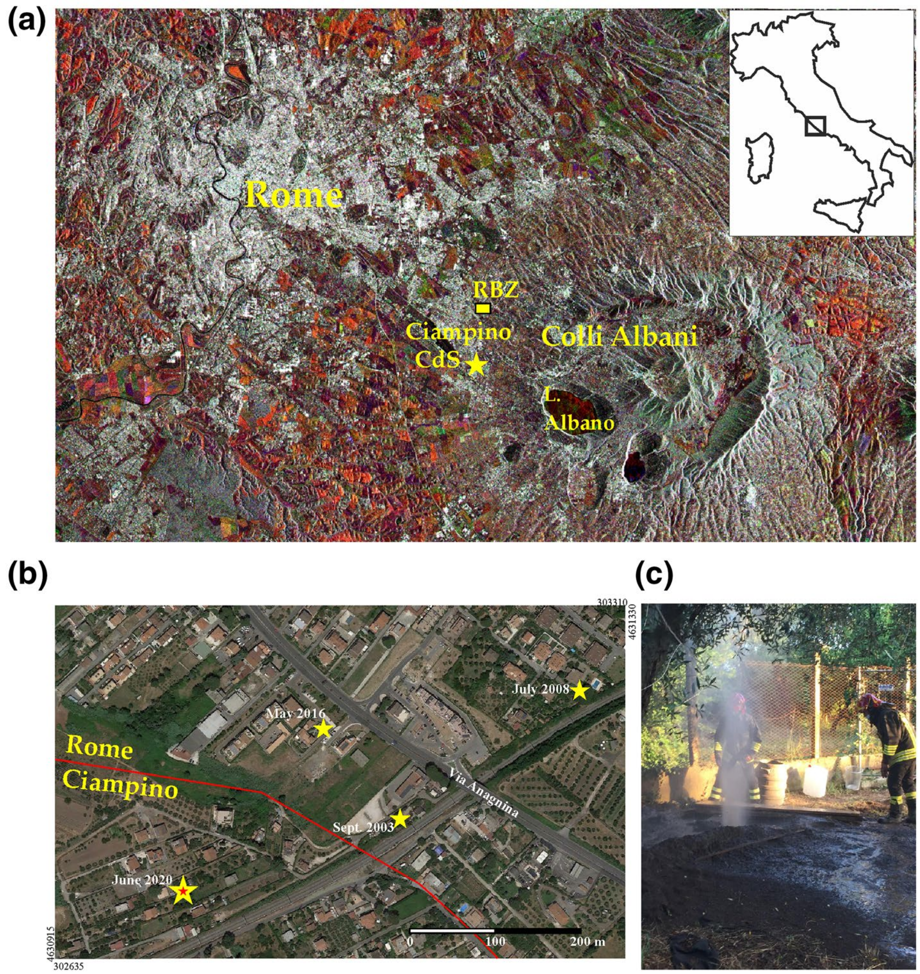

Figure 1. (a) Satellite map of Colli Albani-Rome area. The Albano crater lake (L. Albano), CdS gas discharge and the RBZ are shown. (b) Enlargement of the RBZ rectangle with location of the 2003–2016 gas blowouts (yellow stars); the red star indicates the June 2020 gas blowout. The red line is the boundary between Rome and Ciampino municipalities. (c) The Fire Brigade operating at the 9 June gas blowout. CdS, Cava dei Selci; RBZ, Rome gas blowout zone.

killed many small animals (birds, cats, foxes, and reptiles) and caused the prolonged evacuation of the nearby houses because of hazardous indoor CO_2 gas concentrations (Carapezza & Tarchini, 2007; Carapezza et al., 2010a, 2010b). According to inhabitants, two additional blowouts occurred here during recent drillings.

Colli Albani's youngest craters, CdS gas discharge and RBZ are located near the NW-SE main tectonic lineament of Colli Albani drawn in the structural map of Acocella and Funiciello (2006).

A positive gravity anomaly (Cesi et al., 2008) indicates that the Rome-Ciampino zone is located above a structural high of the carbonate basement, which hosts the regional aquifer of the area (Mazza & Capelli, 2010). The top of the carbonate basement is estimated in this zone to be about 800 m deep. At its summit there is likely a gas cap, confined underneath impermeable allochtonous Ligurian flysch, similar to other volcanic-geothermal contexts of central Italy (e.g., Latera, Chiodini et al., 2007; Torre Alfina, Carapezza et al., 2015).

Carbon dioxide (CO_2) is, after steam, the main gas emitted from active volcanoes and high-medium enthalpy geothermal fields. It is released also diffusively from the soil on the flanks of quiescent volcanoes and in geothermal areas (Burton et al., 2013). CO_2 is an asphyxiant gas denser than air at standard P-T conditions and tends to accumulate in morphological depressions and in house basements. Sudden CO_2

emissions have caused several disasters, as the 1979 phreatic explosion of Dieng plateau, Indonesia (139 deaths, Le Guern et al., 1982) and the CO_2 clouds released from two crater lakes of Cameroon: Lake Monoun, in 1984 with 37 victims (Sigurdsson et al., 1987) and Lake Nyos in 1986 with 1700 deaths (Kling et al., 1987). Hydrogen sulfide (H_2S) is a toxic dangerous gas denser than air, released in low-temperature emissions from volcanic and geothermal areas. Several deaths and adverse health effects caused worldwide, particularly in Italy, Japan, and New Zealand, by inhalation of CO_2 and H_2S are reported in the review of Hansell and Oppenheimer (2005).

On June 9, 2020, a new hazardous gas blowout occurred from a shallow drilling within the RBZ (Figure 1b). Its occurrence confirms the presence in this Rome zone of a dangerous confined gas-pressurized aquifer.

In this paper, we describe the 2020 gas blowout and use newly collected geochemical data to discuss the origin of the gas pressurizing the aquifer and the possible severe increase of the gas hazard, should a seismic or volcanic unrest occur at Colli Albani volcano.

2. Results: The June 9, 2020 Gas Blowout

On June 9, 2020, at about 12 a.m. (GMT), a new gas blowout occurred during the drilling of an unauthorized shallow well in Ciampino municipality, very near to the boundary with Rome municipality and within the RBZ (Figure 1b). The declared depth of the well was 23 m; however, we highlight that the gas pressurized aquifer was found at ∼50 m depth in the very near 2003 well (Figure 1b; Carapezza & Tarchini, 2007). A jet of gas and nebulized water was emitted from the well to 3–4 m height. Dangerous CO_2 and H_2S concentrations were measured near the well, and 12 families were evacuated from their nearby houses. Alerted from the Fire Brigade, our team arrived at 7 p.m. of the same day, to assess the origin and hazard of the gas emission and provide scientific assistance to the emergency services.

The well had a 30 cm diameter and a metallic tube had been inserted in its upper 70 cm. The Fire Brigade placed into the tube a small expansion packer and covered the site with metallic and wood plates. However, the well had not been completely sealed and gas continued to be emitted laterally, outside the packer. To mitigate the gas risk, the Fire Brigade personnel and the members of our team wore, during the fieldwork, a protective gas mask or a light compressed-air breathing apparatus.

2.1. Methods

Gas samples were collected by a funnel placed over the lateral leaks from the well. To ensure the removal of air, gas was repeatedly pumped using a 100 cc syringe by a three-way valve into two-ways Pyrex bottles (with vacuum valves at both sides) where gas was collected. Actually, the O_2 content of the Ci_VV1-2 samples was very low (0.22 and 1.01 vol. %, respectively). Analyses were carried out in the INGV-Palermo labs following the procedure of Paonita et al. (2012).

The soil CO_2 flux was measured with the accumulation chamber method (Chiodini et al., 1998), by a portable West Systems fluxmeter. The device is equipped with an IR Licor-Li820 detector for CO_2 (single-beam dual-wavelength NDIR; range 0–2 vol. %; accuracy: 3% of reading).

Air gas monitoring was carried out by Dräger X-am7000 instruments equipped with IR CO_2 detector (0–100 vol. %; accuracy: 3%) with double beam and temperature compensation, and H_2S electrochemical cell working in the range 0–1,000 ppm (accuracy 5%). The measurements frequency of the continuous recordings was of 1 min.

2.2. Chemistry and Origin of the Emitted Gas

Gas chemical and isotopic composition is reported in Table 1, together with those of the gases emitted in near blowouts, at CdS discharge and from the Lake Albano bottom.

Table 1
Chemical and isotopic analyses of the gas emitted in the RBZ and at CdS

Site	Source	Date d/m/y	He ppm	Ar ppm	N_2 %	CO_2 %	CO ppm	H_2 ppm	H_2S %	CH_4 %	$\delta^{13}C_{CO2}$ ‰ versus. PDB	$^3He/^4He$ R/Ra_c
Ci_VV_ blowout_1	t.p.	10/6/2020	4.8	67	2.26	97.39	b.d.l.	b.d.l.	0.24	0.11	n.a.	1.41
Ci_VV_ blowout_2	t.p.	10/6/2020	4.4	10	2.34	97.33	b.d.l.	b.d.l.	0.21	0.11	0.30	1.59
Rm_VA_blowout	1	19/5/2016	3.3	n.a.	1.48	98.15	b.d.l.	b.d.l.	0.27	0.10	0.65	1.43
Rm_VC_blowout	2	18/10/2003	1.57	n.a.	0.87	98.58	n.a.	7.02	0.50	0.04	1.30	1.90
Cava Selci	3,4	n.r.	4.05	150	0.73	98.53	b.d.l.	2.33	0.68	0.05	0.91	1.54
Cava Selci	5	11/3/2000	2.66	n.a.	0.18	98.98	b.d.l.	b.d.l.	0.80	0.04	1.39	1.46
Cava Selci	6	29/7/2005	1.91	n.a.	0.31	98.84	b.d.l.	b.d.l.	0.80	0.04	0.75	1.34
Cava Selci	7	6/2/2007	2.00	630	0.39	98.57	0.52	b.d.l.	0.93	0.05	0.78	1.44
Dissolved gas	Source	Date d/m/y	He mg/l	O_2 mg/l	N_2 mg/l	CO_2 mg/l	CO mg/l	H_2 mg/l	H_2S mg/l	CH_4 mg/l	$\delta^{13}C$ TDIC	$^3He/^4He$ R/Ra
Lake Albano	8	17/01/06	6.03E-09	1.89E-05	1.11E-02	7.31E-02	b.d.l.	b.d.l.	n.a.	6.08E-03	3.95	1.51

Note. All data have been corrected for air contamination (assuming that O_2 derives from the air).
Abbreviations: CdS, Cava dei Selci; RBZ, Rome gas blowout zone; n.r. = date sampling not reported; n.a. = not analyzed; b.d.l. = below detection limit.
Source: t.p. = this paper; 1. Carapezza et al., 2020a; 2. Carapezza and Tarchini (2007); 3. Giggenbach et al. (1988); 4. $^3He/^4He$ (R/Ra) from Hooker et al. (1985); 5. Carapezza et al. (2003); 6. Barberi et al. (2007); 7. Carapezza et al. (2012); 8. dissolved gas chemistry in Carapezza et al. (2010).

As in all Colli Albani emissions, the gas of the 2020 blowout is dominated by CO_2, with a H_2S content (0.21–0.24 vol. %) slightly lower than in the 2003 blowout (0.50 vol. %) and in the CdS gas (0.68–0.93 vol. %). Also the $\delta^{13}C_{CO2}$ isotopic composition (0.30‰) is slightly lower than in the other Colli Albani gases (0.65‰–1.39‰). The helium isotopic R/Ra_c values measured in the 2020 blowout (1.41 and 1.59) are comparable with those of previous blowouts, CdS gas discharge and dissolved gas in the deep water of Lake Albano (range 1.34–1.90; Table 1). Although very low compared with the $^3He/^4He$ value of the HIMU-like mantle of the Roman Comagmatic Province (R/Ra ~ 7; Martelli et al., 2004 and references therein), the helium isotopic ratio of the Colli Albani gas is similar or even slightly higher that the values found in the fluid inclusions of olivine and clinopyroxene phenocrysts of Colli Albani volcanic rocks (R/Ra = 1.17–1.73; Martelli et al., 2004). For this reason, Carapezza and Tarchini (2007) inferred that the gas has a deep magmatic origin and is released from the Colli Albani magma that had been contaminated with crustal material in the subduction melting process.

In the triangular diagram N_2-He-Ar (Figure 2a), gases show a nearly constant N_2/He ratio and a variable content of argon, which suggests a single gas source region. CdS gases have a higher degree of contamination with air or air-saturated water of a primary deep gas.

The gas samples of the 2020 blowout plot near the N_2 corner, that is, in a position considered by Giggenbach (1991) as representative of the gas of andesitic volcanoes of actively subducting zones. Instead, according to Minissale et al. (1997), the nonatmospheric N_2 of central Italy cold gas emissions has a likely crustal origin. The $\delta^{13}C_{CO2}$ values of the gas (Table 1) suggest that part of its CO_2 is produced either by crustal limestone assimilation in the magma or by decarbonation metamorphic reactions occurred in the deep carbonate aquifer (see Figure 2b). Another possibility is carbonate dissolving from the subducting slab at subarc depths.

2.3. Air Gas Concentration Measurements

On the evening of June 9, high CO_2 and H_2S concentrations were found at 5 m distance from the well: at 30 cm height from the ground (first site) CO_2 = 30 vol. %, H_2S = 965 ppm and at 40 cm height CO_2 = 19 vol. %, H_2S = 520 ppm. On the first site, air gas concentration was continuously measured for nearly half an hour: CO_2 varied from 8 to 16 vol. % and H_2S from 300 to 535 ppm (Figure 3a).

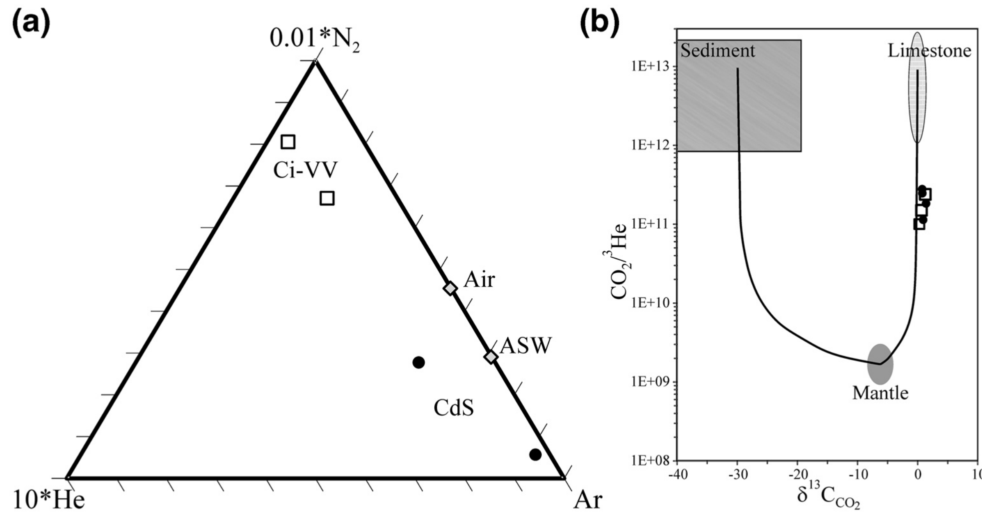

Figure 2. Plot of CdS (black dots) and 2020 blowout (Ci-VV, open squares) gases in (a) N_2-He-Ar triangular diagram and (b) $CO_2/^3He$ versus $\delta^{13}C_{CO2}$ diagram modified after Sano and Marty (1995).

The continuous recording of air gas concentration was repeated on the same site for 1 h25′ in the morning of June 10, finding CO_2 values of 6–16.5 vol. % and H_2S values of 150–665 ppm (Figure 3b). Then the continuous recording station was displaced in a zone more directly affected by the gas jet, at 6 m from the well, where three hooded crows killed by the gas had been found in that same morning (second site in Figure 3b). Here, the atmospheric concentration of both gases was very high: CO_2 = 27–31 vol. %, H_2S always >800 ppm with maxima near to 1,000 ppm.

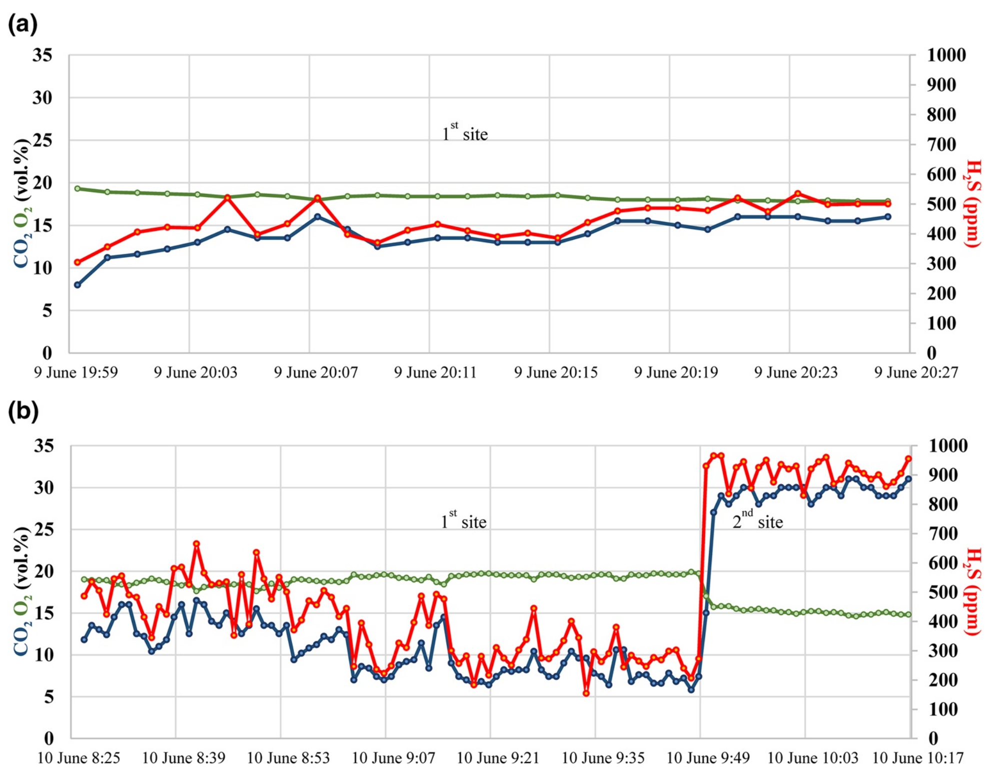

Figure 3. Continuous recording of air gas concentration at 30 cm height near the well. (a) On the evening of June 9. (b) On the morning of June 10. Data set in Carapezza et al. (2020b).

The measured atmospheric CO_2 and H_2S concentrations were extremely dangerous. In fact, the Immediately Dangerous to Life and Health level (i.e., the level that interferes with the ability to escape) is 8.3 vol. % for CO_2 and 100 ppm for H_2S (Barberi et al., 2019 and references therein). As the potentially lethal threshold is ~8 vol. % for CO_2 and 250 ppm for H_2S (IVHHN, 2020) the measured values (CO_2 = 27–31 vol. %; H_2S = 800–1,000 ppm) were immediately lethal to persons and animals.

2.4. Soil CO_2 Flux Investigations

On June 10 morning, a soil CO_2 flux survey was carried out in the zone around the well, with 80 measurements over a rectangular area of ~3,000 m^2. Flux values ranged from 9 to 66,800 g m^{-2} day^{-1}. The threshold of the biological CO_2 flux, that is, the flux generated by soil respiration (Raich & Tufekciogul, 2000), was estimated to be 23 g m^{-2} day^{-1}, the same value estimated by Carapezza and Tarchini (2007) in the near 2003 gas blowout zone. Flux values exceeding this threshold have to be considered of endogenous origin. The total soil flux of endogenous CO_2 was estimated to 1.76 tonnes day^{-1} (i.e., 2.04×10^{-2} kg s^{-1}), with only 1.4% of biogenic flux. The soil CO_2 flux map obtained from the geostatistical processing of the data (Figure 4a) shows that the emitted gas was diffusing in the surficial permeable layers of the terrain, creating an anomalous zone around the well with flux values from 10,000 to over 66,000 g m^{-2} day^{-1}, as observed in all similar circumstances (Barberi et al., 2007; Carapezza & Tarchini, 2007; Carapezza et al., 2010a).

At about 2 h45' p.m. (GMT) of June 10, the emission of gas and water suddenly ceased because of the observed collapse of the well walls. Measurement repetition showed that in only 30′ soil CO_2 flux had diminished by over two orders of magnitude. Such a rapid decrease confirms the high permeability of the shallow soil around the well and indicates that the collapse had likely occurred near the gas releasing aquifer, somewhat restoring its pristine impermeable cover.

Because of a heavy rain, a new soil CO_2 flux survey, on June 11, could be completed only around the well. The related flux map (Figure 4b) showed that the soil gas release had strongly diminished with anomalous values (up to 405 g m^{-2} day^{-1}) persisting only near the well.

The soil CO_2 flux maps of the surveys carried out on June 13, 15 and 22 (Figures 4c–4e) showed a further progressive decrease of soil gas release. The total flux of endogenous CO_2 decreased from 1.76 to 0.009 tonnes day^{-1} (i.e., from 2.04×10^{-2} to 1.04×10^{-4} kg s^{-1}) from June 10 to 22, with CO_2 flux per unit surface decreasing from 0.24 to 0.012 kg m^{-2} day^{-1} (Figure 4f; i.e., from 2.78×10^{-6} to 1.39×10^{-7} kg m^{-2} s^{-1}).

3. Well Cementation

On the morning of June 11, the Fire Brigade removed from the well the covering plates and the expansion packer. It was observed that the terrain around the metallic tube had been deeply eroded by the strong water and gas emission, leaving a 2 m wide caving. The cement filling of the well and the caving was made on the morning of June 13, pouring 4 m^3 of quick-setting cement, the last m^3 weighted by sand addition. After well cementation, the soil CO_2 flux fell down to nearly biological values (Figure 4). The evacuated families were allowed to return home on June 15.

4. Discussion

The south-western part of Rome city hosts a shallow confined gas-pressurized aquifer, which produces hazardous gas blowouts when perforated by drillings.

The lack at Colli Albani of high-temperature fumaroles can be explained with the specific hydrogeological setting of the volcano (Carapezza & Tarchini, 2007), which is characterized by a cold meteoric recharge that feeds permeable levels at various depths (Mazza & Capelli, 2010). Such an extensive cold water circulation obscures any convective or diffused heat flux from depth and actually the Falcognana slim hole drilled in 1986 found only 41°C at 610 m depth (ENEL, 1990).

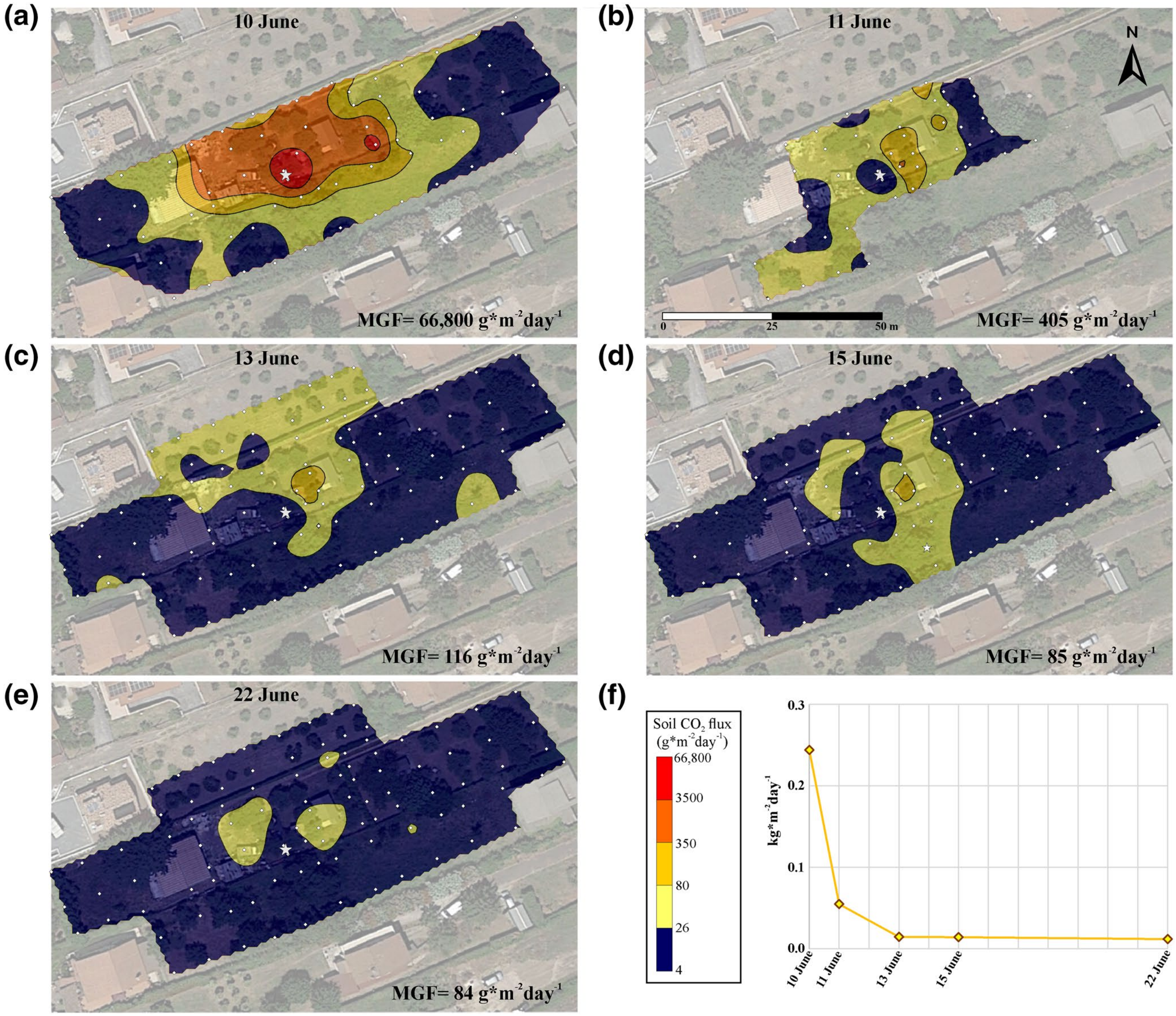

Figure 4. Soil CO_2 flux maps obtained from the five surveys carried out from June 10 to 22, 2020 ((a) to (e)). The white star indicates the well that produced the June 9 gas blowout. White small dots are the measurement points. The maximum soil CO_2 flux value (MGF) measured in each survey is indicated in the relative map. (f) Time variation of endogenous soil CO_2 flux per unit surface. Data set in Carapezza et al. (2020b).

Besides the emission of gas with a magmatic imprint, Colli Albani volcano is characterized by episodic seismic crises, such as the 1989–1990 swarm with more than 3,000 events with $1.5 \leq Md \leq 4.0$, and hypocenters distributed within a NW-SE striking ellipsoidal seismic belt of 6×12 km centered on the western part of the volcano, where the most recent eruptive activity occurred (i.e., Lake Albano; Amato et al., 1994; Trasatti et al., 2018). During this seismic swarm, anomalous release of CO_2-rich fluids was recorded (Chiodini et al., 2012). Leveling, InSAR and GPS data (Amato & Chiarabba, 1995; Riguzzi et al., 2009; Salvi et al., 2004) indicate that a slow but significant uplift has occurred for at least 30 years, on the western part of the volcano, suggestive of magma accumulation (Trasatti et al., 2018).

A future increase in magma accumulation rate can lead to volcanic unrest, characterized by anomalous seismicity, increased ground uplift, and flux of magmatic gas. This gas could further pressurize the confined shallow aquifer of the RBZ, potentially culminating in phreatic explosive activity if the pressure exceeds the strength of the impermeable rock cover (Barberi et al., 1992). Alternatively the unrest might enhance fracturing thereby promoting surface emission of magmatic steam, CO_2 and sulfur species, reducing the likelihood of phreatic explosions but nevertheless posing a significant threat to air quality in this densely populated area.

5. Conclusions

The gas blowout of June 2020 confirms that the boundary zone between Rome and Ciampino contains a confined shallow aquifer (~50 m depth), pressurized by magmatic gas rising from depth, which produces a gas blowout when it is perforated by a well. This is the fourth incident recognized in this zone since 2003, and the people living nearby had to be evacuated from their houses for several days. The gas emitted by the 2020 blowout consisted mostly of CO_2 along with a small but significant amount of H_2S (0.22 vol. %). The atmospheric abundances of both gases exceeded lethal thresholds killing a number of birds. The gas has a magmatic helium isotopic signature and derives from the magma reservoir of the quiescent Colli Albani volcano.

Our findings are a reminder of the volcanic hazard in the Colli Albani and highlight the need for ongoing surveillance of the volcano.

Data Availability Statement

The authors confirm that all data used in this paper can be found in Earth-Prints INGV repository at http://hdl.handle.net/2122/13652.

Acknowledgments
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