Tectonics

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Special Section:
Geodynamics, Crustal and Lithospheric Tectonics, and active deformation in the Mediterranean Regions (A tribute to Prof. Renato Funiciello)

Key Points:
- Rome region contains several zones with anomalous and hazardous emission of endogenous gas brought to the surface by deep-reaching faults
- At least 10 dangerous gas blowouts from shallow wells have occurred in the Rome area in the last 30 years
- Alignment of soil gas anomalies and vents indicates that gas raises along faults controlled by buried Mesozoic carbonate structure

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Faulting and Gas Discharge in the Rome Area (Central Italy) and Associated Hazards

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Abstract The area of Central Italy around Rome contains natural gas discharging zones and several others where quarrying or mining excavation removed the impervious superficial layers allowing a free hazardous discharge to the surface of endogenous gas. These gas manifestations are mostly located above buried structural highs of fractured Mesozoic limestones hosting the main regional aquifer and revealed by gravity anomalies. In the last decades, many gas blowouts occurred in this area, from wells whose depth ranged from 10–15 to 350 m. The main component of the emitted gas is CO_2 with minor H_2S; only in a blowout offshore of Fiumicino CH_4 prevailed. Several animals even of large size and two persons were killed by the emitted gas (mostly by H_2S), and nearby houses were evacuated because of dangerous indoor CO_2 concentrations. He and CO_2-carbon isotopes suggest that gas has a deep mantle signature, as indicated for Fiumicino gas by N_2 isotopic composition and $N_2/^{36}Ar$ ratios. Gas rising from depth first accumulates in the buried Mesozoic limestone reservoir, and from there it escapes along deep-reaching faults. On its way to the surface, the gas dissolves into and pressurizes any encountered confined aquifer, which may then produce a gas blowout when reached by wells. The main direction of the gas feeding faults was estimated through the alignment of visible gas emissive points, the shape of the positive anomalies in soil CO_2 flux maps, and new structural-geological observations, finding that they correspond mostly to the main orientation of the underlying limestone structural high.

1. Introduction

The volcanic area of Central Italy, including Rome, is characterized by a thinned continental crust (20–25 km), high heat fluxes (>80 mWm^{-2}), and a very strong degassing of CO_2 of deep provenance (Chiodini et al., 2004; Gambardella et al., 2004, and references therein). Gas rising from depth has a magmatic or mantle signature (Carapezza & Tarchini, 2007; Chiodini et al., 2004) and dissolves into geothermal aquifers hosted in buried fractured Mesozoic limestones and in shallower cold aquifers hosted either in Neogene clastic sediments and in Quaternary volcanic rocks. All these aquifers release CO_2 (and H_2S)-rich gasses (CH_4-rich gas in the Fiumicino zone) toward the surface mostly along extensional faults, originating many discrete gas discharges or zones of high CO_2 diffuse emission from the soil. The quantity of CO_2 (and associated H_2S) released into the atmosphere reaches locally so high levels to represent a serious hazard to people and animals (Carapezza, Barberi, et al., 2010; Carapezza, Ricci, et al., 2010; Carapezza et al., 2012, and references therein). Also in zones where there is no significant gas release at the surface because of the presence of an efficient cover of impervious rocks, the existence at shallow depth of a gas-pressurized aquifer is revealed by the relatively frequent occurrence of dangerous gas blowouts during drilling (Table 1).

The aims of this work, with the help of original geochemical and structural data, are to (i) describe the geological and geochemical aspects of the main gas discharges of the Rome area, (ii) review the gas blowout episodes occurred in this region in the last decades, and (iii) discuss the tectonic setting to identify those faults through which the deep gas rises to the surface creating hazardous conditions.

The paper is dedicated to the late Prof. Renato Funiciello, with whom we had the privilege of sharing many interesting discussions on the origin and significance of the gas discharges of Central Italy.

2. Geological Setting

Rome is located between two Quaternary volcanoes belonging to the alkali-potassic Roman Comagmatic Province: Albani Hills to the southeast and Mts. Sabatini to the northwest (Figure 1). Volcanic activity

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Table 1
Recent Gas Blowouts From Wells in the Rome Region

Date (d/m/y)	Site	Scope of the well	Depth from surface (m)	Level hosting the pressurized aquifer	References
30/1/1986	700 m SW from L. Albano	Geothermal gradient	230	Pleistocene sands	(ENEL, D. P. T., 1990)
27/9/2003	Rome Via Valle Cupella	Water research	55	Alban Hills loose tephra	Carapezza & Tarchini (2007)
9/2/2005	Fiumicino Isola Sacra	Electric cabin earthing	28	Tiber delta sands and gravels	Barberi et al. (2007)
23/5/2006	Marino S. Maria Mole	Scientific research	~350	Pliocene sands	Mariucci et al. (2008)
16/5/2008	Marino Cava dei Selci	Geognostic borehole	10–15	Alban Hills loose tephra	(Carapezza, Barberi, et al. (2010); Carapezza, Ricci, et al. (2010)
2/7/2008	Rome Via Vervio	Water research	41	Alban Hills loose tephra	Carapezza, Barberi, et al. (2010); Carapezza, Ricci, et al. (2010)
24/08/2013	Fiumicino Coccia di Morto[a]	Electric cabin earthing	35	Tiber delta succession (sands and gravels)	Carapezza et al. (2015)
06/09/2013	Fiumicino Coccia di Morto[a]	Electric cabin earthing	40	Tiber delta succession (sands and gravels)	Carapezza et al. (2015)
27/09/2013	Fiumicino 400 m offshore	Geognostic borehole	31 from sea bottom	Tiber delta succession (sands and gravels)	Carapezza et al. (2015)
12/05/2016	Rome Via Anagnina	Water research	~69	Alban Hills loose tephra	This paper

[a]Represented by the same star in Figure 2.

began at both volcanoes around 600 ka and an important magmatic pulse occurred around 400–300 ka with ignimbritic eruptions followed by caldera collapses (Barberi et al., 1994; Giordano et al., 2010). All Albani Hills magmas have a high-potassium (HK) affinity, whereas at Mts. Sabatini also potassic (K) magmas have been erupted. Phreatomagmatic and hydromagmatic explosive eruptions of primitive magmas characterize the most recent phase of activity of each volcano. The eruptive history, the recurrent seismicity and ground deformation crises, and the likely magmatic origin of the emitted gas suggest that Albani Hills are to be considered a quiescent volcano and future volcanic events cannot be excluded (Carapezza, Barberi, et al., 2010, and references therein). The volcanic products of both areas overlie postorogeny Neogene marine sediments, which in turn cover allochtonous flysch deposits overthrusted atop a thick Mesozoic carbonate rock succession (see geological profiles in Figure 1). These carbonates, permeable by fracturation, host the main regional aquifer of Central Italy, which is often a geothermal reservoir (Cataldi et al., 1995).

Most CO_2-rich gas emissions discharge from the top or flanks of buried structural highs (horsts) of the carbonate substratum, as evidenced by positive gravity anomalies, and where most gas blowouts also occurred (Figure 2). At Fiumicino, on the Tyrrhenian coast (Figure 1), along the littoral plain of the Tiber delta (mainly consisting of Pleistocene-Holocene sediments; Milli et al., 2013), well drilling at shallow depth recently produced gas blowouts (Barberi et al., 2007; Carapezza et al., 2015).

High-angle NW-SE oriented normal faults are evident along the axis of the Apennine chain; conversely toward west, normal faults are covered by Quaternary volcano deposits and recognized only by deep boreholes and geophysical investigations carried out mostly in the frame of geothermal exploration projects (Barberi et al., 1994). Between Rome and the Tyrrhenian coast, seismic profiles have shown the presence of buried NW-SE oriented normal faults (Figure 1; Milli et al., 2013), occasionally associated with elongated positive anomalies of soil CO_2 concentration (Bigi et al., 2014). Along the extensional Tyrrhenian margin, NE-SW transverse tectonic structures also play an important role, either bounding some major extensional basins (e.g., Ardea) or controlling the opening of Quaternary eruptive vents (Acocella & Funiciello, 2006; Faccenna et al., 1994; Mattei et al., 2010).

Geological and gravimetric data indicate that Albani Hills and Mts. Sabatini volcanoes are affected by NW-SE and NE-SW directed faults; a N-S fault of regional importance crosses the Albani Hills volcano (Acocella & Funiciello, 2006; Di Nezza et al., 2008; Giordano et al., 2010; Figure 1).

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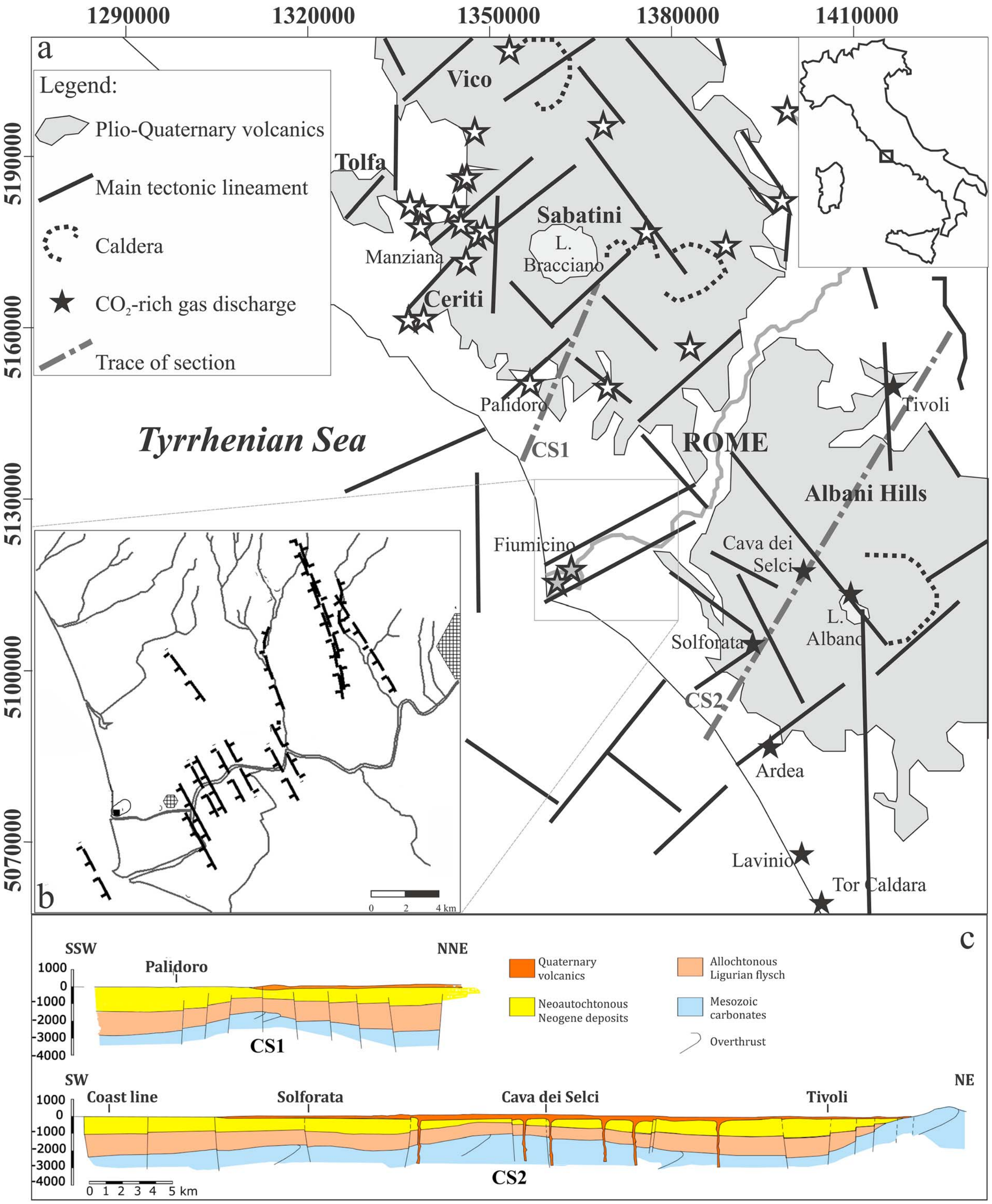

Figure 1. (a) Main tectonic lineaments of the Rome region (modified after Acocella & Funiciello, 2006) and location of CO_2-rich gas discharges from Albani Hills (black stars), from Mts. Sabatini (white stars) and from Fiumicino (gray stars); CS1 and CS2 are the traces of the geological profiles of Figure 1c. Coordinates WGS 1984 Web Mercator (Auxiliary Sphere). (b) Buried main faults of the zone between Rome and Fiumicino, inferred from seismic profiles (after Milli et al., 2013). (c) Geological structure of the Rome area illustrated by (CS1) NNE-SSW geological profile north of Rome passing through the Palidoro gas discharge of Mts. Sabatini and (CS2) NE-SW geological profile south of Rome passing through the Solforata and Cava dei Selci gas discharges of Albani Hills. Profiles were obtained from geological and geophysical data and deep exploratory geothermal wells (modified after Enel, Eni-Agip, Cnr, & Enea, 1987).

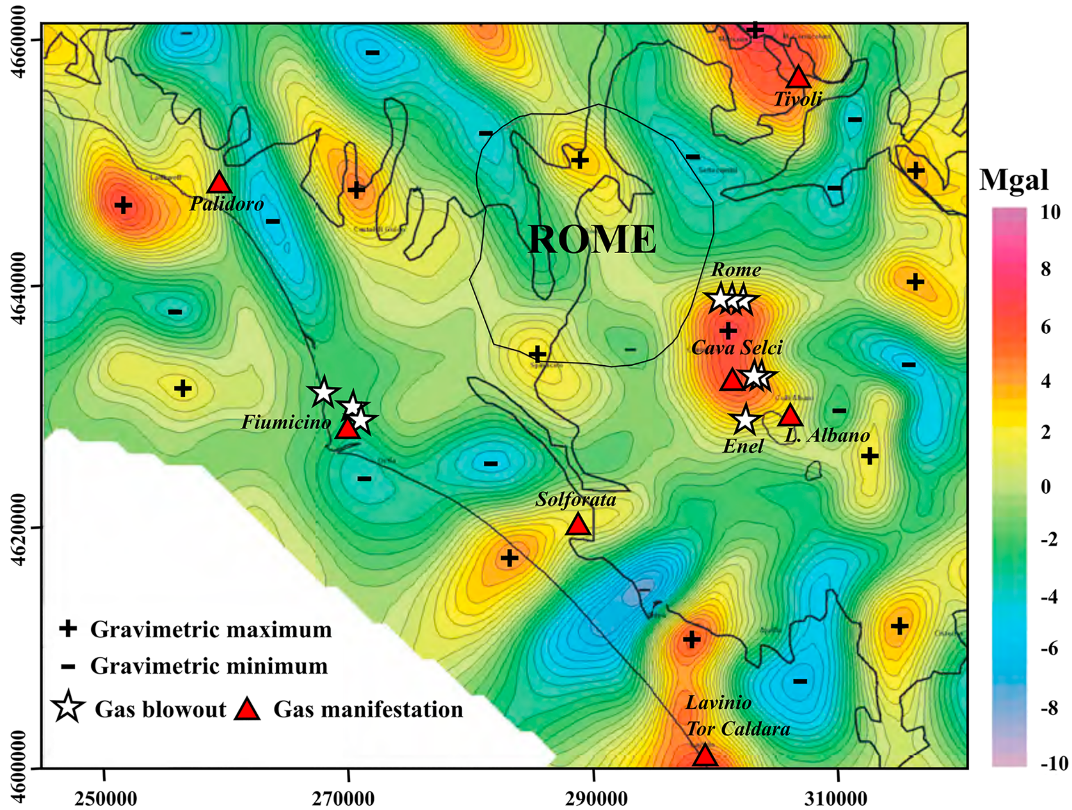

Figure 2. Bouguer gravity anomaly map of the Rome region (after Cesi et al., 2008) with indication of the main manifestations of CO_2 (H_2S)-rich gas discharge and of the gas blowouts occurred in the last 30 years. Coordinates UTM-WGS84-33N.

3. Main Zones of Anomalous Emissions of Endogenous Gas

Both Albani Hills and Mts. Sabatini host a number of CO_2(H_2S)-rich gas discharges (Figure 1). On the Albani Hills side, such gas emissions occur both at the periphery of the volcano (i.e., Tivoli to the north, Tor Caldara-Lavinio to the south, and Solforata to the south-west) and a few kilometers NW of the central crater (Lake Albano), that is, Cava dei Selci (Figure 2). Gas emissions also occur from the bottom of Albano Lake crater and on its eastern border (Carapezza et al., 2008). It is noteworthy that the most important and dangerous gas emissions of Albani Hills are located where stone quarrying (e.g., Cava dei Selci) or sulfur mine excavation (e.g., Solforata and Tor Caldara) removed the superficial levels, including the impervious ones, such as Holocene lahar deposits generated by water overflows from Albano crater lake (De Benedetti et al., 2008; Carapezza, Ricci, et al., 2010), allowing the gas to freely discharge into the atmosphere. These gas manifestations are distributed above three buried carbonate highs, as evident from the Bouguer anomaly map (Figure 2), trending from the Albano crater lake to NW (Cava dei Selci), to SW (Solforata), and to SSW (Tor Caldara).

Also Palidoro gas discharge is located on the eastern flank of a positive Bouguer anomaly (Figure 2) corresponding to a carbonate structural high.

There is no positive gravity anomaly in the zone of Fiumicino. A recent seismic reflection profile carried out across the Tyrrhenian coast in the Fiumicino area, in conjunction with a geochemical survey of soil CO_2 concentration, shows that CO_2 anomalies are NNW-SSE elongated and correspond to normal faults displacing the Tiber delta sequence (Bigi et al., 2014; see section 3.6).

3.1. Albano Lake

Albano maar is the most recent crater of Albani Hills (Anzidei et al., 2007). The lake is hosted within coalescent craters, arranged on an ellipse, formed by hydromagmatic eruptions in Holocene times. The direction of the major axis is NW-SE, corresponding to that of the underlying structural high of the carbonate basement,

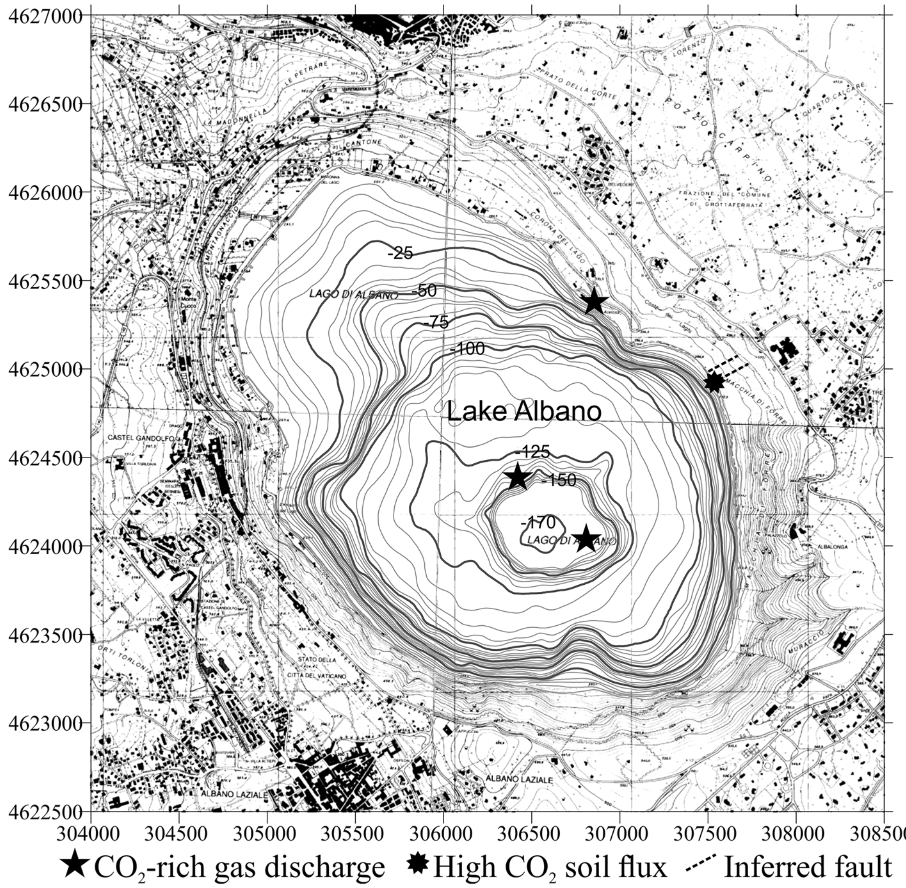

Figure 3. Location of the CO_2-rich gas discharges on the bottom and eastern rim of Albano crater lake. Coordinates UTM-WGS84-33N. The zone to the SE of Acqua Acetosa with the highest soil CO_2 flux (up to 500 g/m^2/day) is marked with an asterisk. The inferred NE-SW faults nearby may extend to the deepest zone of the crater (modified after Carapezza et al., 2008).

whose bordering faults are the main pathways for the deep gas escape (Carapezza et al., 2003). The lake maximum depth ranges between 160 and 170 m. The lake underwent strong level changes and overflows during the Holocene, possibly related to lake rollovers triggered by injections of hot and CO_2-rich fluids from the bottom of the lake. The most recent of these events occurred in the IV century B.C. (described by Plutarcus and Titus Livius) when Romans excavated a drainage tunnel that kept the lake level 70 m below the crater rim (Funiciello et al., 2002, 2003). A significant CO_2-rich gas emission occurs from the lake bottom (Cioni et al., 2003), having a magmatic signature as indicated by $^3He/^4He$ in dissolved gas (R/Ra = 1.30; Carapezza et al., 2008). A similar He isotopic composition (R/Ra = 1.28) was found in the Acqua Acetosa CO_2-rich vent on the eastern border of the lake (Carapezza & Tarchini, 2007; Figure 3).

3.2. Cava dei Selci

Cava dei Selci is a small-excavated depression seasonally hosting a stagnant water pool, where cows and sheep have been killed by gas while drinking (Carapezza et al., 2003). Gas is released convectively from the depression through small discrete vents, and the related total CO_2 viscous flux amounted to 37 tons per day in the highly emissive 2000 winter, when the total diffuse soil CO_2 flux was estimated to 61 tons per day from the entire Cava dei Selci area (12,000 m^2; Carapezza et al., 2003). Ten years of geochemical monitoring and investigations have shown significant time variation in the diffuse soil CO_2 output from a target area of 6,350 m^2 (ranging from 25 to ~3 tons per day, with oscillations). In February 2007 the total diffuse soil H_2S flux from the target area was estimated to 84 kg/day (simultaneous soil CO_2 flux was 10.4 tons per day).

Although the emitted gas is dominated by CO_2 (~98 vol%) and contains 1–1.5 vol% of H_2S (see Table 2), geochemical data demonstrated that H_2S is the killing gas, as it reaches frequently lethal air concentrations (>450 ppm) at 25 cm from the ground (Carapezza, Barberi, et al., 2010; Carapezza et al., 2012). The areal distribution of the main soil gas flux anomaly (Figure 4) indicates that the gas emission is controlled by a NW-SE oriented fault zone, having the same direction of the underlying buried horst of the carbonate basement.

3.3. Solforata

Solforata (Rome municipality) is known since long time for the emission of rotten eggs smelling sulfur gas. This gas discharge is located on the NW border of the Pliocene-Pleistocene Ardea basin, a NE-SW elongated tectonic depression (Faccenna et al., 1994), located above a NE-SW oriented structural high of the buried Mesozoic limestones (see gravimetric map in Figure 2). Mining excavations created small lakes and ponds and removed the impervious superficial layers, allowing free surface discharge of deep gas (see section 5 for gas geochemistry).

Alignment of the gas emitting vents, indicated in the westernmost lake by trains of rising gas bubbles, and the geometry of soil CO_2 flux anomalies (Carapezza et al., 2012) indicate that main degassing is controlled by a NE-SW trending fault zone (Figure 5a). New field observations and photogeological interpretation indicate that main tectonic lineaments are oriented NE-SW and NNE-SSW, but NW-SE lineaments are also well represented (Figures 5b and 5c).

The diffuse soil CO_2 output varies with time, as it was estimated to 46 tons per day from 55,000 m^2 in 1996 (Chiodini & Frondini, 2001), 61.2 tons per day from 30,000 m^2 in 2003 (highest recorded output), and 44 tons per day from 192,000 m^2 in 2007 (Carapezza et al., 2012, and references therein). In the latter survey, the diffuse soil H_2S flux was estimated to 0.5 tons per day from 97,000 m^2 and the viscous (convective) gas release from discrete vents was estimated to 5.4 and 0.04 tons per day for CO_2 and H_2S, respectively (Carapezza, Barberi, et al., 2010; Carapezza et al., 2012).

Dead animals (foxes, cats, wild pigs, and birds) are frequently found in a narrow artificial channel near the westernmost lake (Figure 6), where lethal air H_2S concentrations were measured up to 343 ppm (mean value on a 118-m-long Tunable Diode Laser (TDL) profile; Carapezza et al., 2012).

3.4. Tor Caldara-Lavinio

Tor Caldara gas discharge occurs within a regional natural park located on the Tyrrhenian coast ~24 km SSW of Albano Crater Lake (Figure 1). The sulfur deposits of the zone were extracted for centuries leaving two depressions (Miniera Grande and Miniera Piccola) where the main gas emissions are found. Degassing is particularly high in the eastern part of Miniera Grande, where N-S aligned vents (small mamilliform knolls with sulfur incrustations) can be observed, above degassing fractures (Figures 7a and 7b).

In August 2005 a soil CO_2 flux survey was carried out at Miniera Grande, a few days after the M = 4.7 Anzio earthquake of 22 August 2005, with epicenter near to Tor Caldara. A total soil CO_2 diffuse flux of 11.50 tons per day was estimated from a surface of 15,700 m^2. A new survey in July 2009 showed that diffuse degassing had strongly diminished with a total soil CO_2 flux of only 1.53 tons per day from 11,400 m^2. In July 2009 soil H_2S flux was first measured finding values up to 14.5 $g/m^2/day$ (Carapezza et al., 2012). Finally, a wider and detailed soil CO_2 flux survey was carried out in March–July 2012, covering the whole Tor Caldara area. The total diffuse soil CO_2 flux was estimated to 1.9 tons per day, confirming that the 2005 earthquake produced a temporarily significant degassing anomaly.

Endogenous gas emitted at Tor Caldara and Lavinio, a site on the Tyrrhenian coast a few kilometers to NW (Figure 1) has the highest H_2S content (up to 6.3 vol%) of all gas discharges of the Rome region (see Table 2). So this gas is very dangerous for people and animals, as the lethal H_2S air concentration (450 ppm) is frequently reached near ground. At Lavinio in 2011, a man died and another one suffered permanent health damages while they were working at an underground pool cleaning system located near a CO_2 and H_2S leaking old well.

At 15 cm above the most emissive Tor Caldara vents, air H_2S concentration frequently reaches 500 ppm (the upper detection limit of the devise used by Carapezza et al., 2012), which is an immediately lethal

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Table 2

Chemical and Isotopic Analyses of the Gas Emitted From the Main Manifestations and Well Blowouts of the Rome Region

Locality date (day/month/year)	Ref.	CO_2, vol.%	H_2S, vol.%	CH_4, ppm	N_2, vol.%	H_2, ppm	He, ppm	CO, ppm	Ar, vol.%	O_2, vol.%	$\delta^{13}C$-CO_2, ‰ vs. PBD	$^3He/^4He$, Rc/Ra
Cava dei Selci (CDS)												
14/11/1981	A	97.5	2	400	0.33	3	3	n.a.	n.a.	n.a.	1.2	n.a.
1996–1997	C	97.33	0.67	440	0.82	2.3	4	n.a.	0.015	0.253	0.91	1.54
13/03/2000	E	99.80	0.80	420	0.18	n.a.	3.0	n.a.	n.a.	n.a.	1.39	1.46
10/03/2004	F	98.92	1.20	390	0.47	n.a.	2.2	n.a.	n.a.	n.d.	n.a.	1.38
29/07/2005	I	98.54	0.80	420	0.50	n.d.	1.90	n.d	n.a.	0.05	0.75	1.34
06/02/2007	I	98.58	0.93	452	0.39	n.d.	1.97	0.52	0.063	<0.004	0.78	1.44
30/06/2008	I	98.61	0.62	451	0.64	n.d.	2.44	<0.1	0.104	n.d.	1.18	1.45
29/03/2010	I	98.64	0.90	450	0.31	n.a.	2.3	n.a.	n.a.	0.037	0.87	1.42
Well blowouts near CDS												
S.M.Mole 23/5/2006	I	94.49	0.0005[a]	2,528	5.92	71.28	43.4	0.055	0.015	0.001	−0.53	0.89
Maciocco 2 15/3/2010[b]	I	98.55	0.35	490	0.64	n.d.	2.60	n.a.	n.a.	0.073	0.85	1.37
Maciocco 36 S4 27/6/2008	I	98.47	1.10	574	1.05	<0.0015	2.52	0.10	0.104	n.d.	1.12	1.41
Maciocco 36 -S2 30/6/2008	I	92.77	0.35	606	0.80	0.02	2.62	0.10	0.153	n.d.	1.03	1.51
Well blowouts in Rome												
V. Valle Cupella 18/10/2003	H	98.25	0.50	440	0.87	7.0	1.56	n.d.	n.a.	n.a.	1.30	1.90
V. Anagnina 19/5/2016		96.05	0.26	966	1.84	n.d.	5.92	n.d.	0.035	0.10	0.65	1.43
Solforata												
1981–1982	A	97.6	1.07	150	1.28	<0.001	9	n.a.	0.003	<0.001	3.50	0.95
16/03/2000	F	99.20	n.a.	110	0.80	n.d.	5.30	n.d.	n.a.	0	1.23	0.95
21/09/2004	F	98.91	1.13[a]	90	0.87	n.d.	8.10	n.d.	n.a.	0	n.a.	0.94
08/02/2007	I	92.70	1.20	114	6.08	<7	7.43	0.48	0.014	<0.005	1.05	0.91
Tor Caldara-Lavinio												
Lavinio 1981–1982	A	94.2	4.65	1,500	0.98	<0.001	2	n.a.	0.005	n.d.	−0.5	n.a.
Lavinio -	B	93.3	6.3	510	0.34	0.9	1.3	n.a.	n.a.	0.01	n.a.	n.a.
Tor Caldara 10/7/2009	I	92.80	6.00	1,200	1.01	<5	n.a.	0.60	n.a.	0.08	n.a.	0.27[c]
Fiumicino												
Palidoro 10/19/2011		96.47		8,200	2.11	n.d.	n.d.	0.85	n.a	0.17	n.a.	n.a.
Palidoro 18/10/2013	L	97.00	2.2[a]	8,000	1.24	n.d.	1.47	n.d.	0.0066	0.11	−1.8	0.18
Can. Vignole 12/12/2013	L	95.60		19,900	1.94	n.d.	2.27	n.d.	0.006	0.11	−1.5	0.13
Well blowouts in Fiumicino												
Isola Sacra 1/2/2005	G	98.40	0.001[a]	8,000	1.56	0.05	1.70	0.08	0.001	0.02	−1.5	0.31
Coccia Morto V1 3/9/2013	L	98.10		8,700	1.40		1.56		0.0052	0.08	−1.4	0.22
Coccia Morto V2 10/9/2013	L	98.20		8800	1.27		1.50		0.0037	0.04	−1.5	0.21
Offshore 27/9/2013	L	23.40		595,000	16.90		32.00		n.a.	0.10	−1.6	0.15

Note. PBD = the measure unit of $\delta^{13}C$; n.a. = not analyzed; n.d. = below detection limit: Data after A = Giggenbach et al. (1988); B = Principe et al. (1994); C = Minissale et al. (1997); D = Chiodini and Frondini (2001); E = Carapezza et al. (2003); F = Carapezza et al. (2005); G = Barberi et al. (2007); H = Carapezza and Tarchini (2007); I = Carapezza et al. (2012); L = Carapezza et al. (2015).
[a]Measured on the field with Dräger X-am 7000. [b]Gas leakage from old well. The chemical composition of offshore gas is corrected for atmospheric contamination assuming that all O_2 except 0.1% is atmospheric. [c]Measured on a sample collected on 7/9/2011.

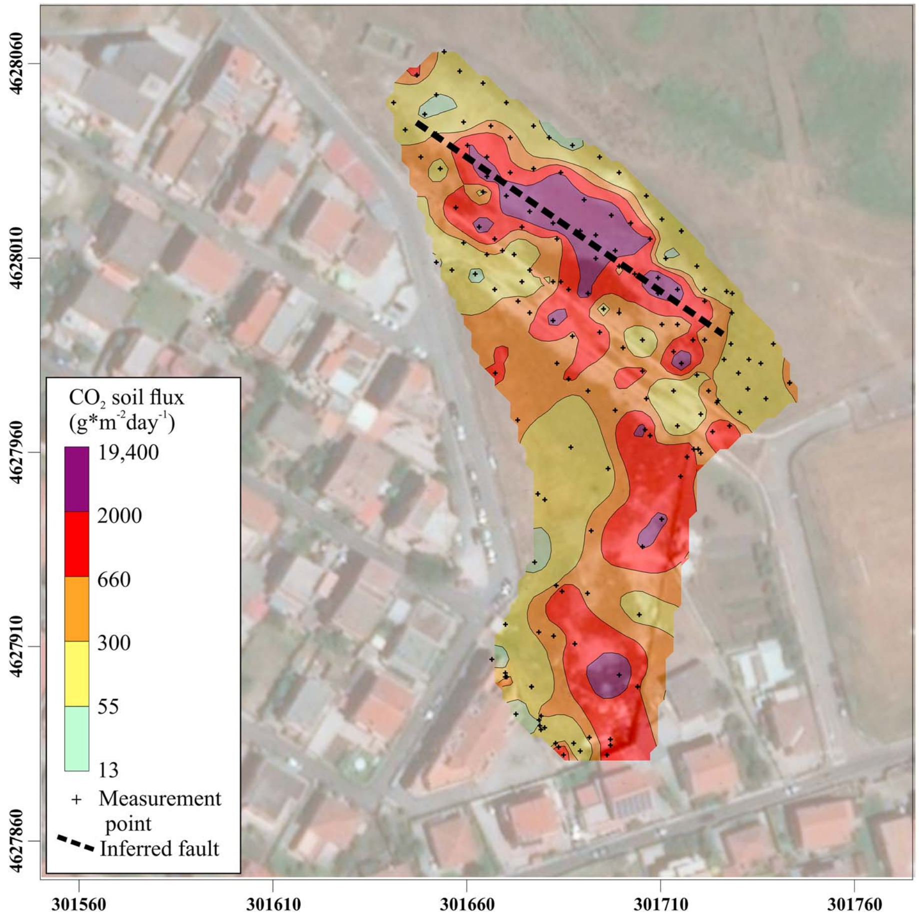

Figure 4. Map of the diffuse soil CO_2 flux of Cava dei Selci (July 2009). Coordinates UTM-WGS84-33N. The total CO_2 flux was estimated to 8.6 tons per day from a surface of 8,700 m^2. Note the proximity to houses of the gas discharge. Dotted line is the NW-SE inferred fault controlling the main gas discharge (modified after Carapezza et al., 2012). The NE-SW alignment of anomalous CO_2 flux values is due to the presence of a buried ditch. The southernmost rounded anomaly corresponds to the boreholes that caused the 2008 blowout.

value. Also air CO_2 concentration attains locally lethal values, although less frequently than H_2S (Carapezza et al., 2012).

New field observations and photogeological interpretation indicate that tectonic lineaments are mostly N30° and N-S oriented in the northern and central part of Tor Caldara, whereas in the southern part E-W and N60° directions prevail (Figures 7c and 7d).

3.5. Palidoro

Palidoro is another important gas discharge of the Rome region; it is located near the Tyrrhenian coast about 20 km to the north of Fiumicino, at the SW periphery of Mts. Sabatini (location and geological section in Figure 1). The main gas emission occurs within a small subcircular depression open on one side and where a small river originates, fed mostly by the resurgence of water (and gas) near the center of the depression (Figure 8a). The high gas hazard of the site is demonstrated by the presence of carcasses of animals of even big size, like dogs and wild pigs (Figure 6h).

The emitted gas contains 97.6 vol.% of CO_2 and 2.2 vol.% of H_2S (Table 2). In May 2007, the viscous (convective) gas flux was estimated in 3.8 tons per day of CO_2 and 0.07 tons per day of H_2S from nine vents, using a floating platform and a volumetric counter (Figure 8a; method description in Carapezza et al., 2012). On the same time, the mean air gas concentration was measured for 3 hr at 25 cm height above the main gas emission site, along a 9-m-long TDL profile (location in Figure 8a; results in Figure 8d). H_2S mean content frequently exceeded potential lethal value (>250 ppm) up to 375 ppm. As these are mean concentration

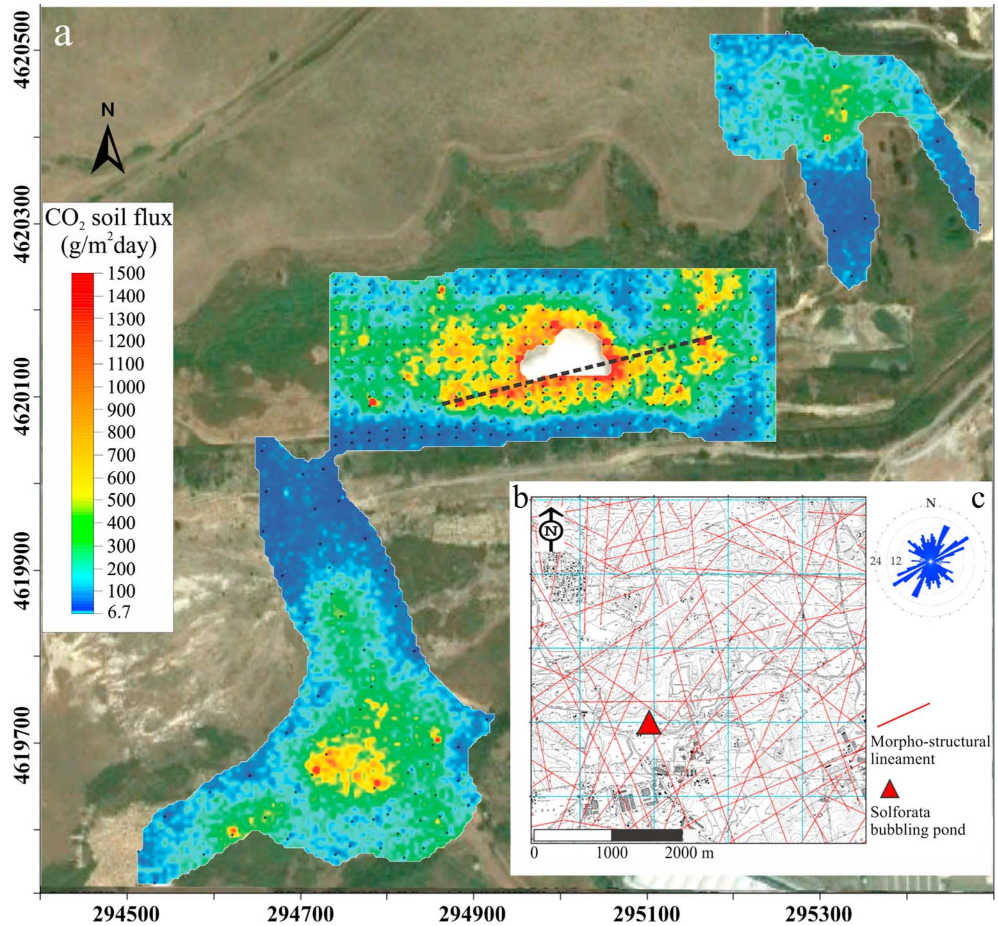

Figure 5. (a) Soil CO_2 flux map of Solforata (May 2007; modified after Carapezza et al., 2012). Coordinates UTM-WGS84-33N. Black dashed line is the main NE-SW degassing fault inferred from geochemical anomalies. (b) Tectonic lineaments obtained from new photogeological interpretation and field observations of the area around the main gas discharge (red triangle); in (c) the related Rosette plot.

values, it can be easily inferred that in some points along the 9-m profile, H_2S air concentration had immediately lethal values (>450 ppm). During the measurements, air CO_2 concentration (max 1.5 vol.%) remained always below hazardous values (lethal concentration ≥ 8 vol.%), confirming that also at Palidoro the killing gas is H_2S.

A new structural analysis over a surface of 15 km^2 around the main gas emission site, based on field observations and aereal photogeological interpretation, shows that the main lineaments are N-S and N40° oriented (Figures 8b and 8c). However, a NW-SE fault seems to affect the main degassing site.

The lack of any vegetation above a NW-SE elongated large area, located to the south and SE of the main gas emission, suggests that anomalous degassing preventing vegetal growth is widespread. In March 2012 we measured in the southeasternmost not vegetated surface, 500 m from the main discharge, high soil CO_2 and H_2S flux values, up to 3,600 and 12.3 g/m^2/day for CO_2 and H_2S, respectively. At 50-cm depth in the soil, we measured CO_2 and H_2S concentrations up to, respectively, 84 vol.% and to the upper limit of the used devise (500 ppm).

3.6. Fiumicino

Fiumicino is located SW of Rome at the mouth of Tiber river (Figure 1). Volcanic deposits of Mts. Sabatini and Albani Hills crop out N and E of Fiumicino, respectively. Several gas blowouts from shallow boreholes

Figure 6. Examples of anomalous gas discharges and gas blowouts of the Rome region with carcasses of animals killed by the gas. (a) Solforata artificial channel with TDL devise; (b) water and gas blowout from Rome—Via Vervio (2008); (c) and (d) fox and cat killed by 2003 blowout of Rome—Via Valle Cupella; (e) cat at Cava dei Selci; (f) carcasses in the Solforata channel; (g) hedgehog at Tor Caldara; (h) wild pig at Palidoro.

occurred in recent years both onshore in the town and offshore, 400 m from the coast (Table 1). The littoral plain of the Tiber delta is made by Pleistocene-Holocene sediments, whose stratigraphy includes three units separated by unconformity surfaces (Milli et al., 2013). The lowermost unit consists of clay and silty clay of Lower Pleistocene belonging to the Monte Mario Sequence. The middle unit consists of gravels and sandy gravels of the middle Pleistocene Ponte Galeria Sequence whose top is found at a variable depth (from −40 to −80 m); this is the most permeable layer hosting a ground aquifer where gas rising from depth may accumulate. The uppermost unit is made of clay and pity clay of the Upper Pleistocene-Holocene Tiber depositional sequence, which acts as an impervious caprock for Ponte Galeria Sequence gravels allowing gas pressurization. The gas rises along NW-SE trending buried faults, revealed by seismic profiles (see inset in Figure 1) and associated to elongated anomalies of CO_2 soil concentration (Figure 9; Bigi et al., 2014).

The gas discharged by the onshore blowouts of 2005 (Barberi et al., 2007) and 2013 (Carapezza et al., 2015) consists mostly of CO_2 (97 vol.% on average) with minor CH_4 ($\leq$1.33 vol.%), whereas the offshore discharged gas has a dominant CH_4 content (59.5 vol.%, with CO_2 = 23.4 vol.%; Table 2).

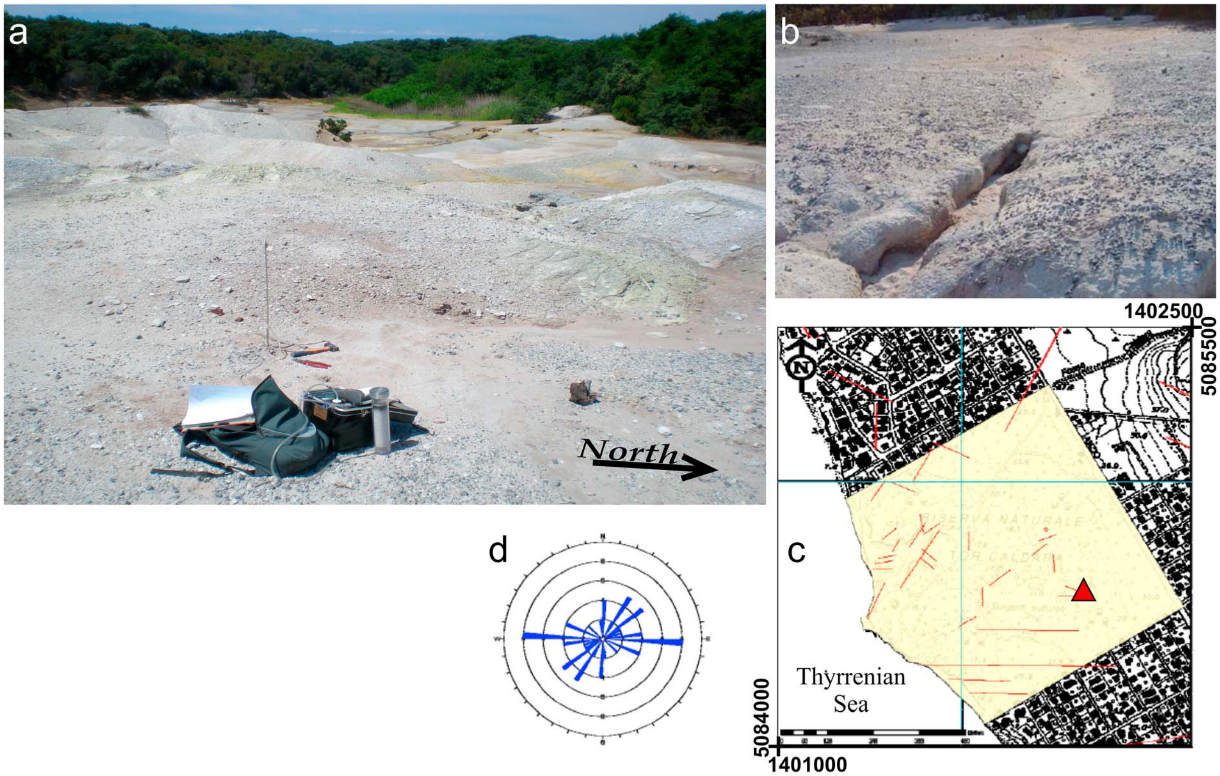

Figure 7. Tor Caldara degassing area of Miniera Grande (red triangle in c): (a) aligned degassing vents with sulfur incrustation, (b) structural element. (c) Structural lineaments of the Tor Caldara regional park (coordinates WGS 1984 Web Mercator—Auxiliary Sphere) and (d) related Rosette plot.

4. Gas Blowouts From Wells in the Rome Region

Since 1986 and up to 2016, 10 gas blowouts from wells have occurred in the region of Rome. The related relevant information is summarized in Table 1, and well locations are indicated in Figure 2. Wells depth from the surface (or from sea bottom) varies from only 10–15 m (Cava dei Selci, 2008) down to 350 m (S. Maria delle Mole, 2006). The geological characteristics of the layer hosting the pressurized aquifer include Pliocene or Pleistocene sands, loose tephra from Albani Hills, and Tiber delta gravels and sands in Fiumicino onshore and offshore wells. Wells have been drilled for different scopes: geothermal gradient measurement, scientific research, geognostic data collection, electric cabin earthing, and water research (Table 1). Only in the two deepest wells the drilling rigs were equipped with blowout preventer (ENEL, D. P. T., 1990; Mariucci et al., 2008). In all other cases gas discharged freely into the atmosphere killing some animals (cats, foxes, and birds) near the wellheads (Figure 6). In addition, gas frequently flowed from the well within the superficial loose soil reaching nearby houses that had to be temporarily evacuated, because of indoor dangerous CO_2 concentration, up to the well closing by cement injection (e.g., Fiumicino Isola Sacra, 2005; Barberi et al., 2007; Carapezza, Ricci, et al., 2010; Rome Via Vervio, 2008; Figure 6b; Rome Via Anagnina, 2016).

Most of the gasses discharged from well blowouts have the same chemical and isotopic composition of those emitted at Cava dei Selci and Solforata (Table 2); Tor Caldara-Lavinio gas has a higher H_2S content (up to 6.3 vol%), and the gas emitted from Fiumicino 2013 offshore well has a high CH_4 content (59.5 vol%; see discussion in section 5).

4.1. Anomalous Gas Emissions From Old Wells

Many old wells of the Rome region, particularly at Cava dei Selci and Fiumicino, produced gas emission during drilling (Novarese, 1926; Ventriglia, 1990; Figures 10 and 11). These wells were abandoned without carrying out any proper well cementation work. Gas leakage from these wells continued along the years, as it is demonstrated by soil gas flux anomalies measured nearby (Giordano et al., 2016), creating hazardous gas

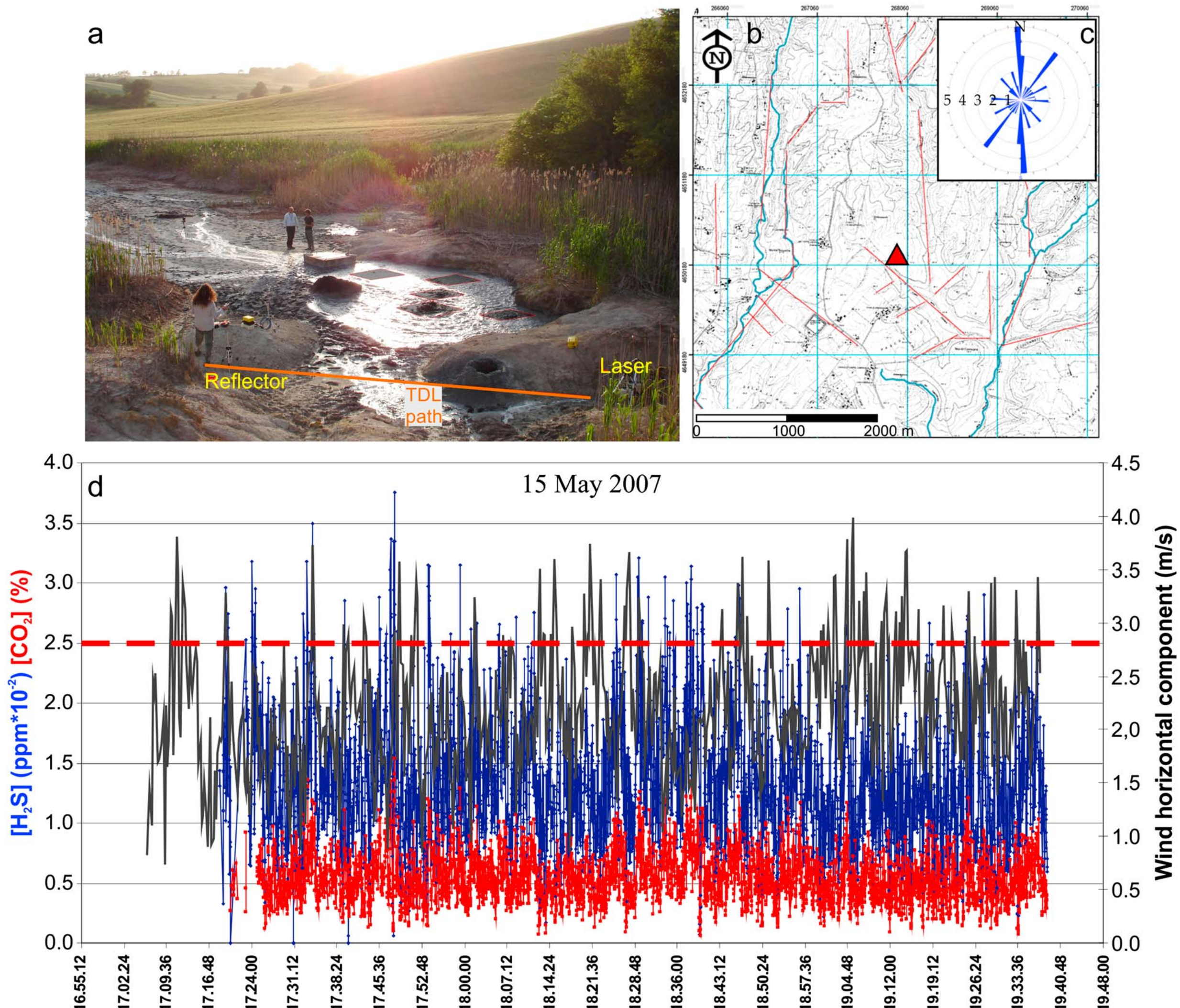

Figure 8. (a) Palidoro spring with strong gas discharge. The floating device for viscous gas flux measurements is shown. The red line indicates the TDL profile whose results are shown in (d). (b) Structural lineaments of the area around the gas emission site, marked by the red triangle (coordinates UTM-WGS84-33N), and (c) related Rosette plot. (d) Mean air concentration of CO_2, H_2S and wind speed recorded for 3 hr on 15 May 2007, at 25 cm from the ground, along the 9-m TDL profile above the main degassing site. Red dotted line indicates the potential lethal value for H_2S (>250 ppm).

concentration at the surface. No vegetal grow can take place near these old wells, as at S. Maria delle Mole (Figure 10b). Two houses at Cava dei Selci are evacuated since 2010 because of the gas emission from an old water well nearby.

5. Geochemical Evidence of a Deep Origin of the Emitted Gas

Chemical and isotopic analyses of the gas emitted from the main discharges and from well blowouts of the Rome region are reported in Table 2. In the majority of cases, the main component is CO_2, with a concentration up to 99 vol.%. In the gas emitted by the September 2013 offshore blowout at Fiumicino, the dominant component is CH_4 (59.5 vol% in the air-corrected composition of an air-contaminated sample; Carapezza et al., 2015). A high CH_4 content (49.6 vol. %) was also found in the gas discharge of Ponte Galeria near Fiumicino (Figure 11; Barberi et al., 2007). The CH_4 isotopic composition suggests for the Fiumicino offshore methane an origin from microbial CO_2 reduction in peat-rich deposits of the Tiber delta. A mixing of such a source with abiogenic CH_4 released from a geothermal reservoir has been inferred for the methane released from the Fiumicino onshore blowouts (Carapezza et al., 2015). In the other CO_2-rich emissions of the Rome region, methane is likely produced by CO_2 reduction (Tassi et al., 2012).

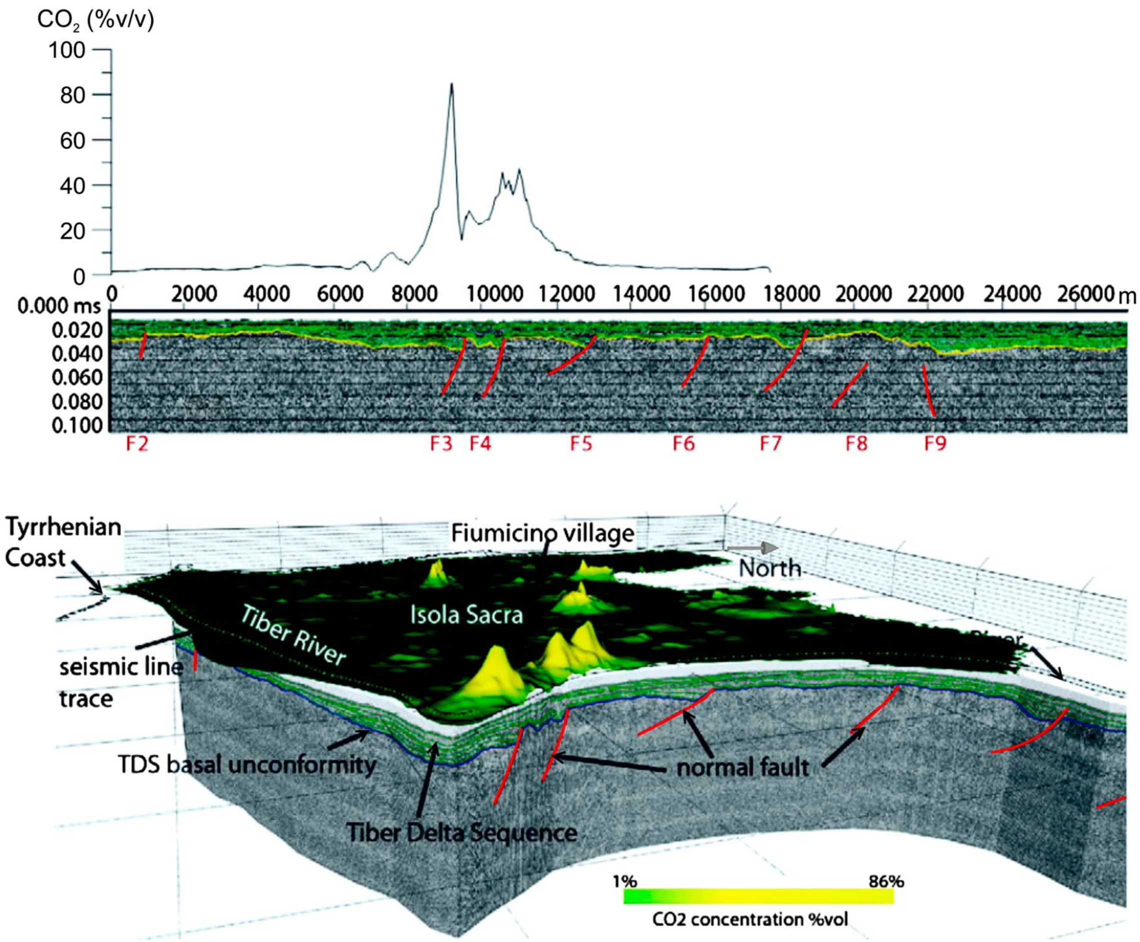

Figure 9. Distribution of CO_2 soil concentration anomalies in the Fiumicino area and location of NNW-SSE buried normal faults (red lines) affecting the Upper Pleistocene-Holocene Tiber delta sequence, identified by seismic reflection profiles (modified after Bigi et al., 2014).

It is clear from the CO_2-CH_4-N_2 triangle of Figure 12a that only the Fiumicino gas has a significant although variable CH_4 content, which is also slightly higher in Lavinio-Tor Caldara emissions with respect to the other gasses of the Rome region. The latter gasses are aligned along the CO_2-N_2 side of Figure 12a, as in most gas manifestations of the Tyrrhenian margin of Central Italy (Minissale et al., 1997), reflecting the relatively wide variations of their N_2 content (0.33–16.9 vol.%; Table 2).

The highest N_2 content was found in the Fiumicino offshore gas and in the gas of the 2013 onshore blowout the N_2 isotopic composition ($\delta^{15}N = 2.9‰$) suggests an appreciable contribution of mantle nitrogen; this is supported also by the $N_2/^{36}Ar$ values (up to 1.72×10^5), which are significantly higher than in air or in air-saturated water (Carapezza et al., 2015).

Figure 12b shows the wide variations of the H_2S content in the Rome region gasses, which ranges from nearly zero at Fiumicino and in one Cava dei Selci blowout, to 6.3 vol.% in Lavinio-Tor Caldara (Table 2). Such a variation likely reflects a variable extent of H_2S oxidation to SO_4^{-2} during interaction with the water of aquifers encountered by the rising gas, as indicated by the sulfurous water springs found in all gas manifestations of the region (Giggenbach et al., 1988).

In the triangle N_2-He-Ar (Figure 12c), the Rome region gasses show a variable degree of contamination with air or air-saturated-water of a primary N_2-rich gas. Gasses plotting near the N_2 corner were considered by Giggenbach (1991) as representative of andesitic volcanoes of actively subducting zones. However, as discussed by Minissale et al. (1997), most of the nonatmospheric N_2 of the cold gas emission of Central Italy has a likely crustal origin from metasedimentary rocks hosting deep aquifers.

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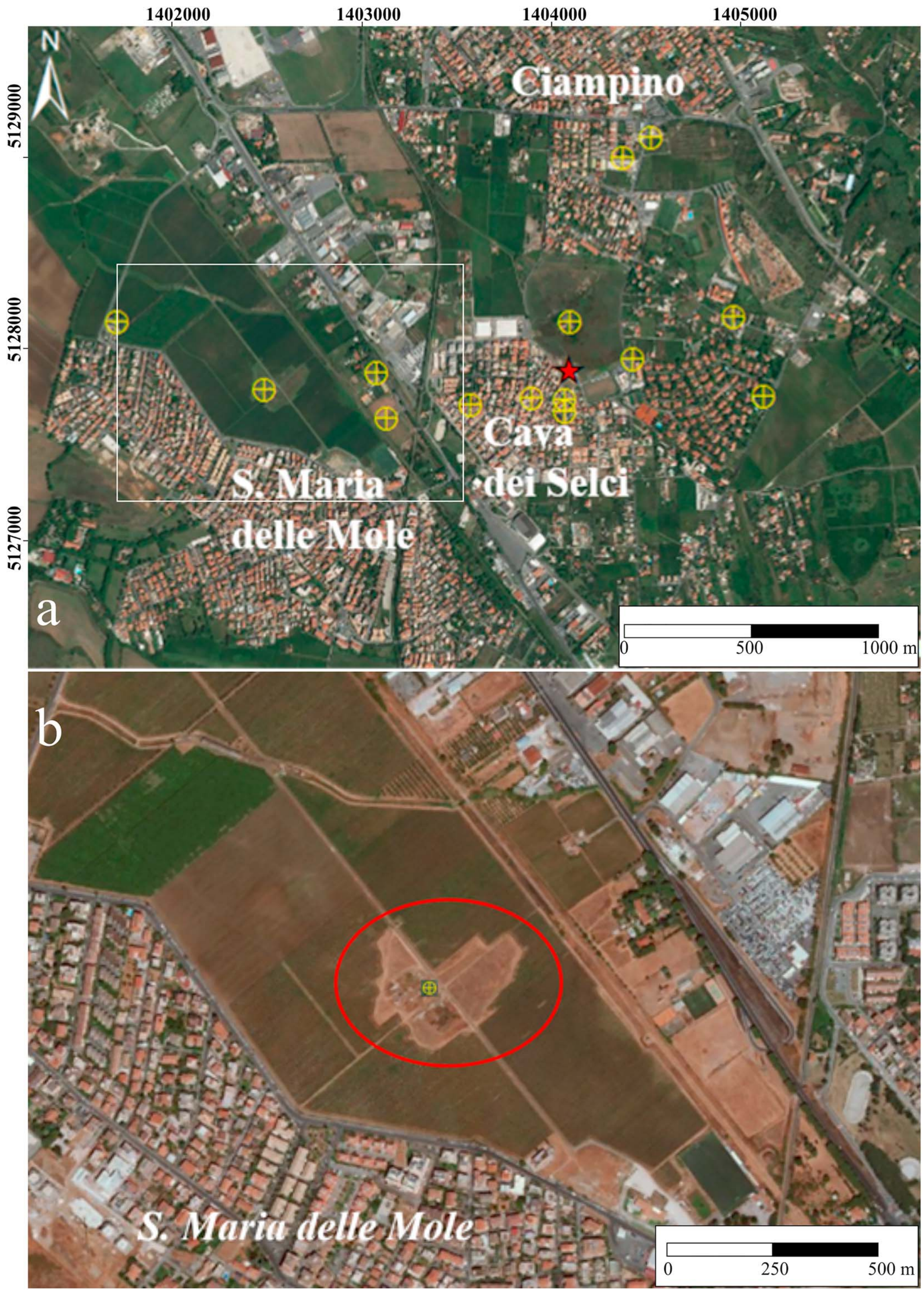

Figure 10. (a) The area around Cava dei Selci with location of the gas manifestation (red star) and of old gas leaking wells (yellow circles). Coordinates WGS 1984 Web Mercator (Auxiliary Sphere). (b) S. Maria delle Mole area, rectangle in (a), with location of an old gas leaking well (yellow circle) that prevents vegetation growth on the neighboring zone (encircled in red).

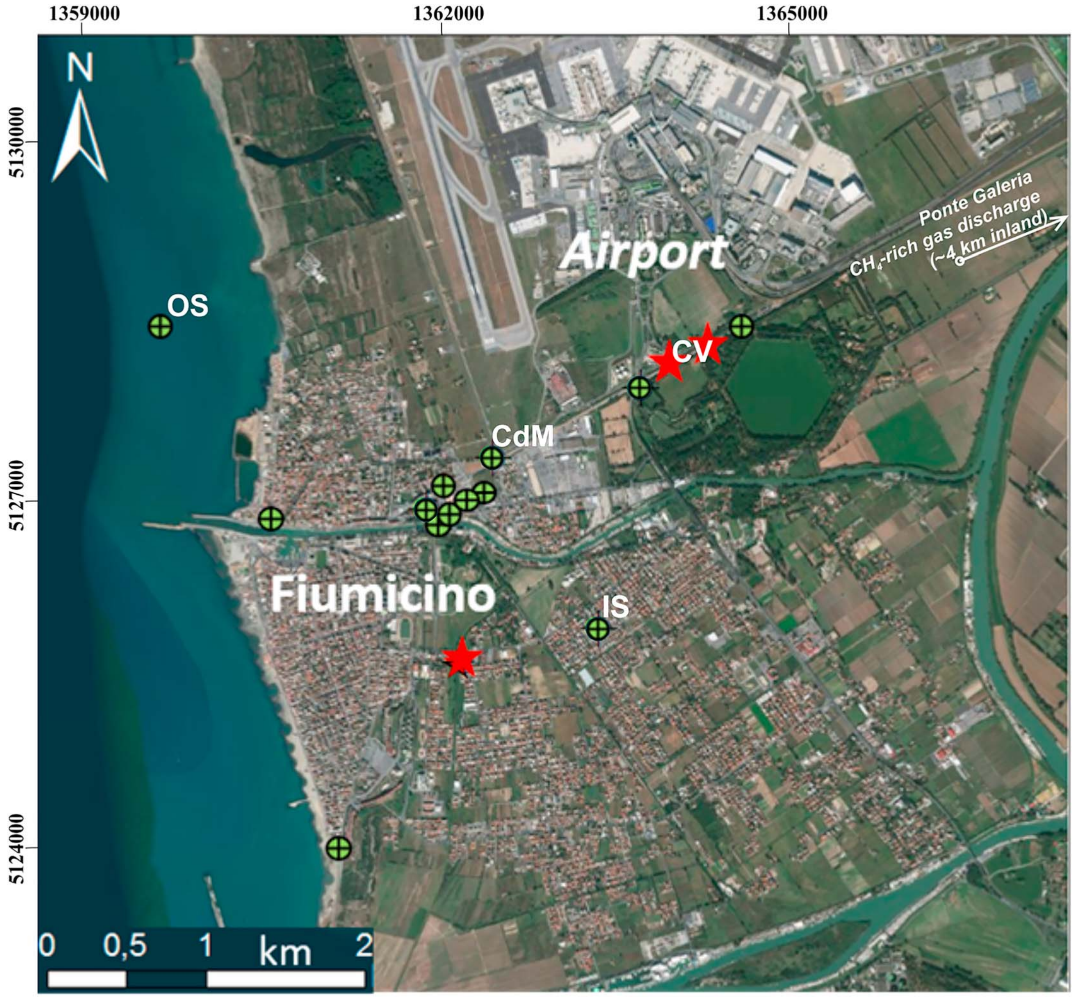

Figure 11. Fiumicino area with location of the gas discharges (red stars) and of blowout producing wells (green dots). CV = Canale Vignole; CdM = Coccia di Morto; IS = Isola Sacra; OS = offshore. Coordinates WGS 1984 Web Mercator (Auxiliary Sphere).

The helium isotopic composition of the Rome region gasses, that is, the $^3He/^4He$ ratio (R) expressed with respect to the same ratio in air (Ra), can be used to discriminate the role of mantle versus crustal sources for these gasses. The R/Ra values of the Rome region gasses range from 0.13 to 1.9. The lowest values (0.13–0.18) are found in the Fiumicino offshore gas and in the near natural manifestations of Canale Vignole (Figure 11) and Palidoro; Rc/Ra increases slightly in the Fiumicino onshore blowouts (0.21–0.31), in Tor Caldara gas (0.27), and in Albano crater lake (0.28–0.30). The highest Rc/Ra values (0.89–1.90) are found in the gas emissions and blowouts nearest to the Albani Hills eruptive center, that is, at Cava dei Selci and in the eastern zone of Rome. These values are significantly lower than that from "typical mantle" (R/Ra ~8.0; Marty & Jambon, 1987). On the other hand, there is a strong geochemical evidence, indicating that the alkali-potassic magmas of the Roman Comagmatic Province originate from either mantle contaminated by subducted crustal component or by slab-derived crustal fluids (Gasperini et al., 2002; Peccerillo & Lustrino, 2005, and references therein). In addition, fluid inclusions in phenocrysts of the volcanic rocks of Central Italy have low R/Ra values, very near to those of the gas manifestations of the same area (Carapezza & Tarchini, 2007; Martelli et al., 2004). These data therefore indicate that most gasses of the Rome region have a deep mantle or magmatic signature, with the ^4He-rich crustal component increasing moving from the zones of Cava dei Selci and eastern Rome toward the Tyrrhenian coast (Palidoro-Fiumicino-Tor Caldara).

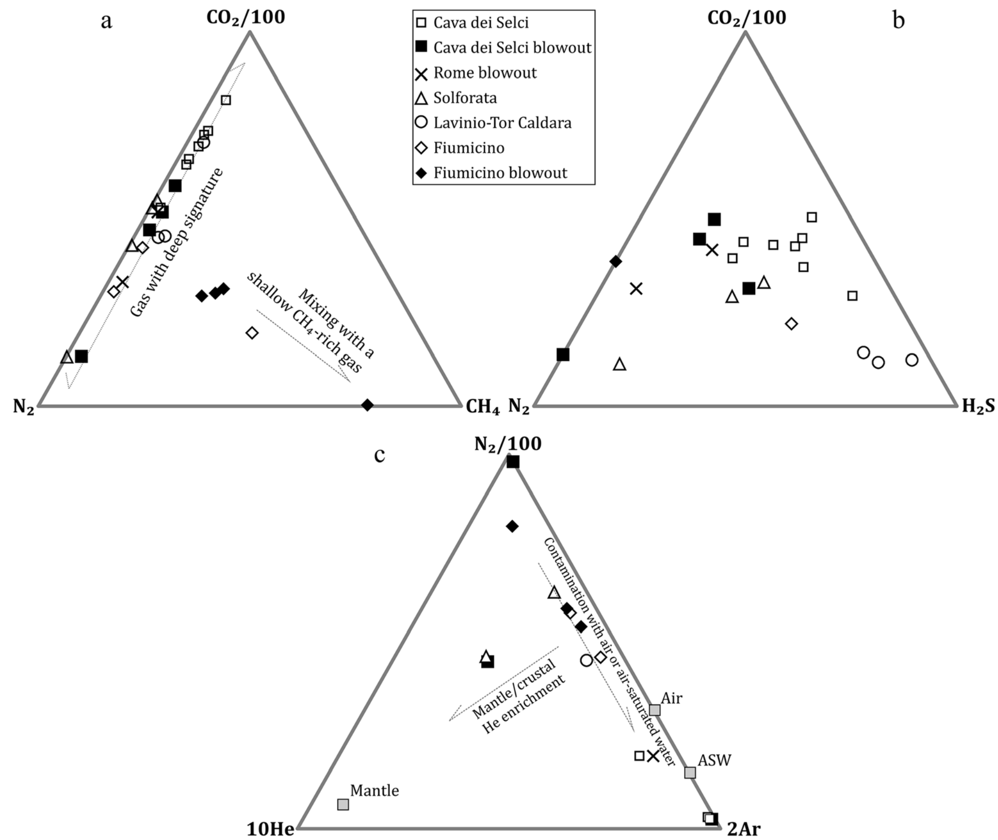

Figure 12. Plot of the gasses from discharges and blowouts of the Rome province in (a) CO_2-CH_4-N_2, (b) CO_2-H_2S-N_2, and (c) N_2-Ar-He triangles.

The isotopic composition ($\delta^{13}C$) of the CO_2 of the Rome region gasses has a rather wide variation (−1.80‰ to +3.50‰ vs. PBD PBD=the measure unit of $\delta^{13}C$; Table 2), which prevents a clear identification of its source (Tamburello et al., 2018). An origin from Mesozoic carbonates has been suggested for the CO_2 of Central Italy gas manifestation (Minissale et al., 1997; Panichi & Tongiorgi, 1976). More convincingly, Chiodini et al. (2000) have shown the presence of a common deep CO_2 source in the western side of the Apennine chain including the Tyrrhenian volcanic zones. Such a deep CO_2 has a $\delta^{13}C$ of about −3‰, compatible with the C isotopic composition of a CO_2 deriving from a crustally contaminated mantle, but not compatible with a derivation from metamorphic decarbonation ($\delta\ ^{13}C_{CO2} > 2‰$). However, the rather positive values of the C_{CO2} isotopic composition of the gasses discharged near Rome suggest a mixing process of a mantle CO_2 with a shallower source.

6. Conclusions

In the area of Central Italy around the city of Rome, there are several zones where the removal of superficial impervious layers by quarrying or mining excavations allows gasses of deep provenance to reach the surface (e.g., Cava dei Selci, Solforata, and Tor Caldara; Figure 1). The emitted gas (mostly CO_2 up to 99 vol.%, with 1–6.3 vol.% of H_2S and 0–59.5 vol.% of CH_4) is denser than air, and when not dispersed by wind, it tends to accumulate near the soil, within depressions, channels, and basements, reaching lethal concentrations (mostly for H_2S), killing animals and also occasionally people and threatening the safety of some near houses that had to be evacuated.

In addition, at least 10 dangerous gas blowouts from mostly shallow wells have occurred in the last 30 years in the same Rome area, up to the Tyrrhenian coast (Table 1) where many old gas-leaking wells are also found (Figures 10 and 11). A few of these wells were located in the proximity of a gas discharge (e.g., Cava dei Selci and S. Maria delle Mole), but most of the blowouts occurred in zones with no evidence at the surface of any gas manifestation (e.g., eastern part of Rome) or where only some anomalous diffuse soil CO_2 flux values had been recorded (e.g., Fiumicino).

The gas emitted by the blowouts has a chemical and isotopic composition similar to that of the gas of the discharges, the only difference being a dominant CH_4 content (59.5 vol.%) in the Fiumicino offshore blowout. Frequently, these gas blowouts killed some animals and caused the prolonged evacuations of nearby houses.

The isotopic composition of the CO_2-rich endogenous gas of the Rome region, particularly its $^3He/^4He$ ratio, indicates the presence of a significant deep mantle or magmatic component, which is particularly evident in the gas emissions nearest to the Albani Hills volcanic center, including Albano crater lake, but is recorded also in Fiumicino and Palidoro gas by the N_2 isotopic composition and the $N_2/^{36}Ar$ ratios. The gas rising from depth first accumulates and equilibrates within buried fractured Mesozoic limestones covered by an impervious flysch; from there it escapes to the surface along faults. Any time that such a fault encounters a shallower confined aquifer, CO_2 dissolves into its water up to oversaturation, pressurizing the aquifer, which is then ready to produce a gas blowout when reached by a well. Blowout information (Table 1) indicates that such gas-pressurized aquifers occur at rather variable depth, from about 350 m to only a dozen meters from the surface.

The alignment of visible gas emissive points, the geometry of surveyed soil gas flux anomalies, and the structural elements derived from new field observations and photogeological interpretations allow to establish that the faults through which gas is transported toward the surface have the following main direction:

1. Cava dei Selci and Albano crater lake: NW-SE.
2. Solforata: NE-SW.
3. Tor Caldara: NNE-SSW; NE-SW; N-S.
4. Palidoro: N-S; NE-SW; NW-SE.

It is of relevant interest to observe that these faults have the same main direction of the underlying carbonate basement as evidenced by gravity anomalies (Figure 2), suggesting that the buried horst and graben structure of the Mesozoic carbonates and their flyschoid cover, characteristic of Central Italy, still controls the present-day gas upraise from these structures to the surface. Only at Fiumicino there is no gravimetric evidence of the presence at depth of a structural high of the carbonatic basement; rising to the surface of deep gas is here controlled by deep-reaching NW-SE normal faults.

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References

Acocella, V., & Funiciello, R. (2006). Transverse systems along the extensional Tyrrhenian margin of Central Italy and their influence on volcanism. *Tectonics*, *25*, TC2003. https://doi.org/10.1029/2005TC001845

Anzidei, M., Carapezza, M. L., Giordano, G., Lelli, M., & Tarchini, L. (2007). New discoveries on the Albano maar lake from high-resolution bathymetry and dissolved CO_2 budget (Colli Albani volcano, Central Italy). *Journal of Volcanology and Geothermal Research*, *171*(3–4), 258–268.

Barberi, F., Buonasorte, G., Cioni, R., Fiordelisi, A., Foresi, L., Iaccarino, S., et al. (1994). Evoluzione geologica dell'area geotermica Tosco-Laziale durante il Plio-Pleistocene. *Memorie descrittive Carta Geologica d'Italia*, *49*, 77–134.

Barberi, F., Carapezza, M. L., Ranaldi, M., & Tarchini, L. (2007). Gas blowout from shallow boreholes at Fiumicino (Rome): Induced hazard and evidence of deep CO_2 degassing on the Tyrrhenian margin of Central Italy. *Journal of Volcanology and Geothermal Research*, *165*(1–2), 17–31. https://doi.org/10.1016/j.jvolgeores.2007.04.009

Bigi, S., Beaubien, S. E., Ciotoli, G., D'Ambrogi, C., Doglioni, C., Ferrante, V., et al. (2014). Mantle-derived CO_2 migration along active faults within an extensional basin margin (Fiumicino, Rome, Italy). *Tectonophysics*, *637*, 137–149. https://doi.org/10.1016/j.tecto.2014.10.001

Carapezza, M. L., Badalamenti, B., Cavarra, L., & Scalzo, A. (2003). Gas hazard assessment in a densely inhabited area of Colli Albani Volcano (Cava dei Selci, Roma). *Journal of Volcanology and Geothermal Research*, *123*(1-2), 81–94. https://doi.org/10.1016/S0377-0273(03)00029-5

Carapezza, M. L., Barberi, F., Ranaldi, M., Ricci, T., Tarchini, L., Barrancos, J., et al. (2012). Hazardous gas emissions from the flanks of the quiescent Colli Albani volcano (Rome, Italy). *Applied Geochemistry*, *27*(9), 1767–1782. https://doi.org/10.1016/j.apgeochem.2012.02.012

Carapezza, M. L., Barberi, F., Tarchini, L., Cavarra, L., & Granieri, D. (2005). Le emissioni gassose dell'area vulcanica dei Colli Albani. Nuovi dati sull'attività recente del cratere del lago Albano e sul degassamento dei Colli Albani. *Atti Acc. Naz. Lincei*, *218*, 229–242.

Carapezza, M. L., Barberi, F., Tarchini, L., Ranaldi, M., & Ricci, T. (2010). Volcanic hazard of the Colli Albani. In R. Funiciello & G. Giordano (Eds.), *The Colli Albani VolcanoIAVCEI Special Publications* (Vol. 3, pp. 279–297). London: Geological Society.

Carapezza, M. L., Lelli, M., & Tarchini, L. (2008). Geochemistry of the Albano and Nemi craters lakes in the volcanic district of Alban Hills (Rome, Italy). *Journal of Volcanology and Geothermal Research*, *178*(2), 297–304. https://doi.org/10.1016/j.jvolgeores.2008.06.031

Carapezza, M. L., Ricci, T., Barberi, F., Ranaldi, M., & Tarchini, L. (2010). Hazardous gas blowouts from shallow wells in the Colli Albani volcanic complex (Rome, Italy). In P. Birkle & I. S. Torres-Alvarado (Eds.), *Water-rock interaction* (Vol. 13, pp. 913–916). Leiden: CRC Press.

Carapezza, M. L., & Tarchini, L. (2007). Magmatic degassing of the Alban Hills volcano (Rome, Italy): Geochemical evidence from accidental gas emission from shallow pressurized aquifers. *Journal of Volcanology and Geothermal Research*, *165*(1–2), 5–16. https://doi.org/10.1016/j.jvolgeores.2007.04.008

Carapezza, M. L., Tarchini, L., Granieri, D., Martelli, M., Gattuso, A., Pagliuca, N. M., et al. (2015). Gas blowout from shallow boreholes near Fiumicino International Airport (Rome): Gas origin and hazard assessment. *Chemical Geology*, *407*, 54–65.

Cataldi, R., Mongelli, F., Squarci, P., Taffi, L., Zito, G., & Calore, C. (1995). Geothermal ranking of Italian territory. *Geothermics*, *24*(1), 115–129. https://doi.org/10.1016/0375-6505(94)00026-9

Cesi, C., Eulilli, V., & Ferri, F. (2008). Analisi ed interpretazione dei valori delle anomalie di gravità del territorio dell'area romana: correlazione con gli elementi geologici di superficie e la struttura profonda. In R. Funiciello, A. Praturlon, & G. Giordano (Eds.), *La Geologia di Roma. Memorie Descrittive della Carta Geologica d'Italia* (Vol. 80, pp. 97–114). Firenze: SELCA.

Chiodini, G., Cardellini, C., Amato, A., Boschi, E., Caliro, S., Frondini, F., & Ventura, G. (2004). Carbon dioxide earth degassing and seismogenesis in central and southern Italy. *Geophysical Research Letters*, *31*, L07615. https://doi.org/10.1029/2004GL019480

Chiodini, G., & Frondini, F. (2001). Carbon dioxide degassing from the Alban Hills volcanic region, Central Italy. *Chemical Geology*, *177*(1-2), 67–83. https://doi.org/10.1016/S0009-2541(00)00382-X

Chiodini, G., Frondini, F., Cardellini, C., Parello, F., & Peruzzi, L. (2000). Rate of diffuse carbon dioxide earth degassing estimated from carbon balance of regional aquifers: The case of Central Apennine, Italy. *Journal of Geophysical Research*, *105*(B4), 8423–8434. https://doi.org/10.1029/1999JB900355

Cioni, R., Guidi, M., Raco, B., Marini, L., & Gambardella, B. (2003). Water chemistry of Lake Albano (Italy). *Journal of Volcanology and Geothermal Research*, *120*(3-4), 179–195. https://doi.org/10.1016/S0377-0273(02)00383-9

De Benedetti, A. A., Funiciello, R., Giordano, G., Diano, G., Caprilli, E., & Paterne, M. (2008). Volcanology, history and myths of the Lake Albano maar (Colli Albani volcano, Italy). *Journal of Volcanology and Geothermal Research*, *176*(3), 387–406. https://doi.org/10.1016/j.jvolgeores.2008.01.035

Di Nezza, M., Di Filippo, M., & Toro, B. (2008). Shallow structure of the Colli Albani Volcanic District from gravity measurements. Paper presented at EUG 5th General Assembly, Vienna, Austria. Geophysical Research Abstracts, Vol. 10, EGU2008-A-09320, 2008, SRef-ID: 1607–7962/gra/EGU2008-A-09320.

ENEL, D. P. T. (1990). Esplorazione geotermica nel P.R. Colli Albani. Internal report, Pisa, 54.

Enel, Eni-Agip, Cnr & Enea (1987). Inventario delle risorse geotermiche nazionali.– (Sezioni Geologiche, Tav. 2. Regione Lazio). Ministero dell'Industria, del Commercio e dell'Artigianato.

Faccenna, C., Funiciello, R., Bruni, A., Mattei, M., & Sagnotti, L. (1994). Evolution of a transfer-related basin: The Ardea basin (Latium, Central Italy). *Basin Research*, *6*(1), 35–46. https://doi.org/10.1111/j.1365-2117.1994.tb00073.x

Funiciello, R., Giordano, G., & De Rita, D. (2003). The Albano maar lake (Colli Albani volcano, Italy): Recent volcanic activity and evidence of pre-Roman Age catastrophic lahar events. *Journal of Volcanology and Geothermal Research*, *123*(1-2), 43–61. https://doi.org/10.1016/S0377-0273(03)00027-1

Funiciello, R., Giordano, G., De Rita, D., Carapezza, M. L., & Barberi, F. (2002). L'attività recente del cratere del Lago Albano di Castelgandolfo. *Rendiconti Scienze Fisiche e Naturali, Accademia Nazionale dei Lincei*, *9*(13), 113–143.

Gambardella, B., Cardellini, C., Chiodini, G., Frondini, F., Marini, L., Ottonello, G., & Vetuschi Zuccolini, M. (2004). Fluxes of deep CO_2 in the volcanic areas of central-southern Italy. *Journal of Volcanology and Geothermal Research*, *136*(1–2), 31–52. https://doi.org/10.1016/j.jvolgeores.2004.03.018

Gasperini, D., Blichert-Toft, J., Bosch, D., Del Moro, A., Macera, P., & Albarede, F. (2002). Upwelling of deep mantle material through a plate window: Evidence from the geochemistry of Italian basaltic volcanics. *Journal of Geophysical Research*, *107*(B12), 2367. https://doi.org/10.1029/2001JB000418

Giggenbach, W. F. (1991). Chemical techniques in geothermal exploration. Application of geochemistry in geothermal reservoir development (pp. 119–144). Rome: UNITAR.

Giggenbach, W. F., Minissale, A., & Scandiffio, G. (1988). Isotopic and chemical assessment of geothermal potential of the Colli Albani area, Latium, Italy. *Applied Geochemistry*, *3*(5), 475–486. https://doi.org/10.1016/0883-2927(88)90020-0

Giordano, G., Carapezza, M. L., Della Monica, G., Todesco, M., Tuccimei, P., Carlucci, G., et al. (2016). Conditions for long-lasting gas eruptions: The 2013 event at Fiumicino international airport (Rome, Italy). *Journal of Volcanology and Geothermal Research*, *325*, 119–134. https://doi.org/10.1016/j.jvolgeores.2016.06.020

Giordano, G., Mattei, M., & Funiciello, R. (2010). Geological map of the Colli Albani volcano (scale 1:50,000). In R. Funiciello & G. Giordano (Eds.), *The Colli Albani VolcanoIAVCEI Special Publications* (Vol. 3). London: Geological Society.

Mariucci, M. T., Pierdominici, S., Pizzino, L., Marra, F., & Montone, P. (2008). Looking into a volcanic area: an overview on the 350 m scientific drilling at Colli Albani (Rome, Italy). *Journal of Volcanology and Geothermal Research*, *176*(2), 225–240. https://doi.org/10.1016/j.jvolgeores.2008.04.007

Martelli, M., Nuccio, P. M., Stuart, F. M., Burgess, R., Ellam, R. M., & Italiano, F. (2004). Helium-strontium isotope constraints on mantle evolution beneath the Roman comagmatic province, Italy. *Earth and Planetary Science Letters*, *224*(3-4), 295–308. https://doi.org/10.1016/j.epsl.2004.05.025

Marty, B., & Jambon, A. (1987). C^3He in volatile fluxes from the solid earth: Implications for carbon geodynamics. *Earth and Planetary Science Letters*, *83*(1–4), 16–26. https://doi.org/10.1016/0012-821X(87)90047-1

Mattei, M., Conticelli, S., & Giordano, G. (2010). The Tyrrhenian margin geological setting: From the Apennine orogeny to the K-rich volcanism. In R. Funiciello & G. Giordano (Eds.), *The Colli Albani VolcanoIAVCEI Special Publications* (Vol. 3, pp. 7–27). London: Geological Society.

Milli, S., D'Ambrogi, C., Bellotti, P., Calderoni, G., Carboni, M. G., Celant, A., et al. (2013). The transition from wave-dominated estuary to wave-dominated delta: The Late Quaternary stratigraphic architecture of Tiber River deltaic succession (Italy). *Sedimentary Geology*, *284-285*, 159–180. https://doi.org/10.1016/j.sedgeo.2012.12.003

Minissale, A., Evans, W. C., Magro, G., & Vaselli, O. (1997). Multiple source components in gas manifestations from north-central Italy. *Chemical Geology*, *142*(3-4), 175–192. https://doi.org/10.1016/S0009-2541(97)00081-8

Novarese, V. (1926). La trivellazione di Fiumicino e le emanazioni di CO_2 del Vulcano laziale. *Bollettino del Regio Ufficio geologico d'Italia*, *51*, 1–9.

Panichi, C. & Tongiorgi, E. (1976). Carbon isotopic composition of CO_2 from springs, fumaroles, mofettes, and travertines of central and southern Italy: A preliminary prospection method of geothermal areas. Paper presented at 2nd UN Symposium Development and Use of Geothermal Energy, San Francisco. Proceeding (pp. 815–825).

Peccerillo, A., & Lustrino, M. (2005). Compositional variations of Plio-Quaternary magmatism in the circum-Tyrrhenian area: Deep versus shallow mantle processes. In G. R. Foulger, J. H. Natland, D. C. Presnall, & D. L. Anderson (Eds.), *Plates, plumes, and paradigms Geological Society of America, Special Paper* (Vol. 388, pp. 421–434). https://doi.org/10.1130/2005.2388(25)

Principe, C., Romano, G. A., & Vannozzi, D. (1994). GEOCH databank: Geochemical data of natural fluids from Italian active volcanoes under surveillance. Reference Manual. *GeoInformatica*, *2*, 75–82.

Tamburello, G., Pondrelli, S., Chiodini, G., & Rouwet, D. (2018). Global-scale control of extensional tectonics on CO_2 earth degassing. *Nature Communications*, *9*(1), 4608. https://doi.org/10.1038/s41467-018-07087-z

Tassi, F., Fiebig, J., Vaselli, O., & Nocentini, M. (2012). Origins of methane discharging from volcanic-hydrothermal, geothermal and cold emissions in Italy. *Chemical Geology*, *310*, 36–48.

Ventriglia, U. (1990). *Idrogeologia della provincia di Roma—Regione Vulcanica dei Colli Albani*, *Amministrazione Provinciale di Roma* (Vol. 3, p. 547). Roma: Abete Grafica.