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Evidence of CO_2-gas emission variations in the central Apennines (Italy) during the L'Aquila seismic sequence (March-April 2009)

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ABSTRACT The occurrence of intense CO_2 degassing processes generating hundreds of cold CO_2-rich gas emissions is typical of the central Apennines. In 2009, significant anomalies were detected coinciding with the L'Aquila seismic sequence as a consequence of a wide degassing process. Over the same time-span, space-time anomalies in Thermal InfraRed (TIR) satellite imagery possibly related to the increase of green-house gas (such as CO_2, CH_4, etc.) emission rates were detected in central Italy during the seismic swarm by a Robust Satellite Technique (RST) data analysis. A gas geochemical survey carried out in the L'Aquila area confirms the deep crustal origin of the anomalous gas emission detected by ground measurements. Anomalous fluid related signals were recorded some days before the mainshock coinciding with the most marked TIR anomalies independently detected by the RST analysis over 3 different types of satellite data. Anomalous gas emissions detected by ground measurements lasted some weeks, putting in evidence relationships with crustal deformative processes associated with the seismic sequence. Together with previous ground observations in the Umbria-Marche area, present ground and satellite TIR observations, are compatible with the hypothesis that a central Apennines area, much wider than the L'Aquila (March-April 2009) epicentral one, was actually affected by anomalous increases in CO_2 release thus providing new tools to better understand the processes occurring behind a seismic shock.

Key words: gas emission, L'Aquila earthquake, TIR.

1. Introduction

The active deformation field of central Italy is mainly characterized by an extension in the axial zone of the Apennines and by contraction in the frontal part of the belt, close to the Adriatic Sea border (Montone and Mariucci, 1999; Pauselli *et al*., 2006).

The Apennine extensional seismotectonic area is a structural domain that has undergone SW-NE extension since the Middle Pliocene. It is presently characterized by active NE-and SW-dipping normal and normal-oblique faults, mainly located along the axial belt of the Apennines, with associated intramontane basins. Relatively frequent earthquakes with moderate magnitude (4.0<*M*<6.0) have been recorded instrumentally over the past 20 years; furthermore, large historical earthquakes with long recurrence intervals occurred in this province. They are mainly located in the upper crust, at depths less than 15 km (Pace *et al*., 2006). Most of the seismicity is associated with low-angle normal faults accommodating uplift of basement culminations generated by active lithospheric thrusts beneath the Apennine watershed (Finetti *et al*., 2001). Apart from the western sector, in the central portion of Apennine chain (along the accretionary wedge), many areas are affected by an intense CO_2 degassing leading to numerous cold, CO_2-rich gas emissions (Minissale, 2004). Besides the main CO_2 component, lesser amounts of N_2, H_2S, CH_4, H_2, Ar, He and CO are the released gas phases. Some of the degassing areas display significant gas flow rates [300-1000 l/s: Italiano *et al*. (2001)]. One of those areas, San Faustino (SF), located close to the Martana Fault, which delimits the eastern margin of the south-western Tiber basin branch and marked by a CO_2-dominated gas release (CO_2, flow rate ~ 6 t/day) was considered for a continuous CO_2 monitoring (Heinicke *et al*., 2011). All data recorded in the period 2009-2010 display considerable modifications in the daily CO_2 flow rate coinciding with the March-April 2009 seismic sequence when a M_w =6.3 seismic event (Chiarabba *et al*., 2009) struck the town of L'Aquila (Abruzzo region) located about 80 km away. Similar modifications in the degassing rate had been recorded in thermal waters located over the Umbria (Triponzo) and Marche (Acquasanta) regions (Italiano *et al*., 2009b) showing that the anomalous increase in the CO_2 release involved a wide area of the central Apennines, much wider than the epicentral area.

In order to assess the possible link among the variations in recorded gas flow rate and seismic events some limiting factors should be considered. Dobrovolsky *et al*. (1979) published a first evaluation of a possible magnitude-distance relation for the maximal distance between hypocenter and the strain induced anomalous phenomena starting from available experimental data. According to Dobrovolsky *et al*. (1979) a possible pre-seismic anomalous signal in the fluid system can be expected if the distance between the epicenter and fluid monitoring site is, for example, less than 19 km for events of magnitude M≤3, 52 km for M≤4 and 141 km for M≤5. Further reviews carried out by Toutain and Baubron (1999), Hartmann and Levy (2005), Cicerone *et al*. (2009) show similar or smaller radii for the occurrence of possible fluid-related precursory phenomena. In this work, a more conservative radius of 100 km has been assumed for the inclusion of seismic events in the correlation-analysis of SF site data.

The increase of green-house gas (such as CO_2, CH_4) emission rates is only one of the models proposed until now, to explain the anomalous space-time fluctuations of the Earth's emitted Thermal InfraRed (TIR) radiation observed from a satellite [see Tramutoli *et al*. (2001), Tramutoli *et al.* (2005) and reference herein] from days to weeks before strong earthquakes. Other (not alternative) models have been proposed to justify such observations, relating them to ascending gas and water (Tronin *et al*., 2002), to Rn emanations (Pulinets *et al*., 2006; Yasuoka *et al*., 2006) causing air ionization, variations of humidity and latent heat exchange variations (Dey and Singh, 2003; Cervone *et al*., 2006; Pulinets *et al*., 2006, 2007, Singh *et al*., 2006), activation of positive-hole pairs in rocks under pressure during rock deformation causing mid-infrared emission at the surface (Freund, 2002, Freund *et al*., 2006). Note that most of the processes mentioned above are in some way related to gas emissions, mainly Rn, CO_2 (which is a carrier of Rn) and CH_4. It is well known that Earth degassing activity (and particularly for optically active gases like CO_2 and CH_4) is generally more intense alongside seismogenic faults (e.g., Irwin and Barnes, 1980). Abrupt variations of such gases in near-surface atmospheric layers could result in a local greenhouse effect[1] that increases near-surface temperature and, consequently TIR emission. Following the description of the preparatory phases of an earthquake given, for instance, by Scholz *et al*. (1973), we could expect that the extensive process of micro-crack formations (consequence of the continuously increasing stress field) supports the increase of such degassing activity that, together with deep-water rise and convective heat flow towards the surface, could contribute to a strongly increased TIR emission by increasing not only near surface temperature but also ground emissivity. When the stress field becomes locally so high as to close the cracks and an earthquake occurrence is approaching, all the above processes (and the TIR emission measured at that time) are expected to be reduced up to the time of earthquake occurrence. In this period of time, as a consequence of major cracks opening in the rupture zone, a new increase of degassing activity (and related phenomena) and TIR emissions is expected before a gradual return to normality. It is worthwhile to remind the reader that the appearance of an intense (from 2 to 100 times its normal concentration) CO_2 degassing activity a few days before strong earthquakes has been a not rare reported occurence (e.g., Qiang et al., 1991; Barka, 1999) in literature. A quantitative estimate of the increase of the Earth's TIR emission, to be expected as a consequence of a boost of atmospheric CO_2 concentration, has been performed by using the Radiative Transfer code MODTRAN[2] by Tramutoli *et al*. (2009) proving that the increase of CO_2 concentration in the lower atmosphere can cause a TIR signal increase (in terms of Brightness Temperature) from a few, to several tens of degrees, in so as far as CO_2 concentration moves from 2 to 20 times its normal level. However, TIR signal increases, even greater than 5 K, can be easily measured as a consequence of the change of only one of the parameters - included by Tramutoli *et al*. (2005) in the list of the main contributor to the natural/observational noise - whose changes are independent from any type of seismic activity. This noise can be as large as (in some cases larger than) the TIR signal variations previously reported in literature, as thermal anomalies, and claimed as precursors of impending earthquakes (Tramutoli *et al*., 2005). For this reason, refined data analysis techniques are required to discriminate actual TIR signal anomalies from its "normal" variations due to changes of *llocal*[3] spatial (i.e., horography, land cover, etc.) or temporal (time of the day, season, etc.) conditions of the Earth's surface (e.g., temperature, humidity, etc.) and atmosphere (e.g., water vapor content and more generally TIR transmittance). The Robust Satellite Technique (RST) approach (Tramutoli 1998, 2007), demonstrated its capability of reducing most of the natural/observational contributions affecting TIR signal variability, thus permitting it to isolate significant, residual

[1] Atmospheric layers of gases, like CO_2 and CH_4, that are mostly transparent with regard to solar radiation and active in absorbing the Earth's emitted infrared radiation can locally operate like a greenhouse: they allow the solar radiation to reach the Earth's surface and warm it up but they contrast the cooling of the Earth's surface by absorbing and re-emitting, the Earth emitted infrared radiation, toward the surface. The result, depending on the local wind regimes, can be observed even at some distance from the gas sources, and produces a warming up of the Earth's surface and near surface atmospheric layers.

[2] MODTRAN (MODerate resolution atmospheric TRANsmission,) is a computer program designed to model atmospheric propagation of electromagnetic radiation for spatial frequencies from far-infrared (100 cm^{-1}) to the deep ultraviolet (50000 cm^{-1}). The MODTRAN Code (Berk *et al*., 1989) calculates atmospheric transmittance and radiance at moderate spectral resolution, primarily 2 cm^{-1} (20 cm^{-1} in the ultraviolet).

[3] According to Tramutoli (1998) the double *l* was introduced, and will be hereafter used, to highlight a reference not only to a specific place *r* but also to a specific time *t*.

anomalous transients, better than any other previous satellite data analysis technique. Their possible space–time relation with earthquake occurrence have always been investigated (on the basis of several years of satellite TIR observations) by using a validation/confutation approach devoted to verifying the presence/absence of such anomalies in the presence/absence of strong seismic events. Since its first application to the November 23, 1980, Irpinia-Basilicata earthquake (Tramutoli *et al*., 2001; Di Bello *et al*., 2004) the RST approach has been applied to dozens of earthquakes (Filizzola *et al*., 2004; Corrado *et al*., 2005; Tramutoli *et al*., 2005, 2009; Aliano *et al*., 2007, 2008a, 2008b; Genzano *et al*., 2007, 2009b) that have occurred in different continents (Europe, Asia, America and Africa) with different degassing regimes.

In this paper, the space-time fluctuations of the Earth's emitted TIR radiation, observed by Genzano *et al*. (2009a), Lisi *et al*. (2010) and Pergola *et al*. (2010) at the time of the Abruzzo earthquake by applying the same technique to different (polar and geostationary) satellite sensors, have been compared with ground observations of CO_2 degassing in order to verify one of the genetic models up to now proposed to explain the occurrence of TIR anomalies in relation with strong earthquake occurrences and, possibly, to obtain further indications on the geographical extension of CO_2 anomalous degassing at the regional scale.

2. Gas geochemistry

Sedimentary rocks present in central Italy allow the intense circulation of deeply originated fluids. In particular, anomalous CO_2 discharges were identified in the area and closely related to the extensional movements of the normal faults responsible for the 1997-1998 Umbria-Marche seismic sequence (Italiano *et al*., 2009a). A multiple origin of CO_2 was proposed by Chiodini *et al*. (2004), Minissale (2004), and Italiano *et al*. (2008) attributed to carbonate hydrolysis, thermometamorphic processes, mantle degassing, and to mechanochemical activity in faulted areas. In particular, the SF gas emission, (Fig. 1) was repeatedly analyzed for geochemical monitoring and equipped with monitoring instrumentation (Heinicke *et al*., 2000, 2011; Italiano *et al*., 2009b).

The chemical composition of SF gas emission is: CO_2 98%, N_2 1.5%, CH_4 0.3%, while helium concentration is in the range 4-12 ppm. Helium and carbon isotopes allowed us to establish that most of the CO_2 emitted is generated in the crust by thermometamorphic and mechanochemical processes (Italiano *et al*., 2008).

Large, potential deep CO_2 reservoirs were identified by Finetti *et al*. (2001) interpreting data of the CROP 03 deep seismic reflection profile cross-section of central Italy. Large high porosity carbonatic reservoirs occur at depth in the range of 1-10 km and may host fluids like water and CO_2 as observed in the close San Donato well where an explorative hydrocarbon well encountered CO_2 at a pressure of about 98 MPa at a depth of 4750 m (Chiodini *et al*., 2004). A crustal origin is attributed to the kind of CO_2, associated to helium with a clear radiogenic-derived signature ($^3He/^4He$ = 0.02 Ra where Ra is the $^3He/^4He$ ratio in air).

Highly pressurized CO_2 is characterized by a physical behaviour similar to water and can mix with water originating poorly compressible deep supercritical fluids. Deep reservoirs filled by non-compressible fluids, may act, in principle, as natural strain meters (Bodvarsson, 1970) and geochemical anomalies observed in SF gas emission during the1997-1998 seismic swarm in gas

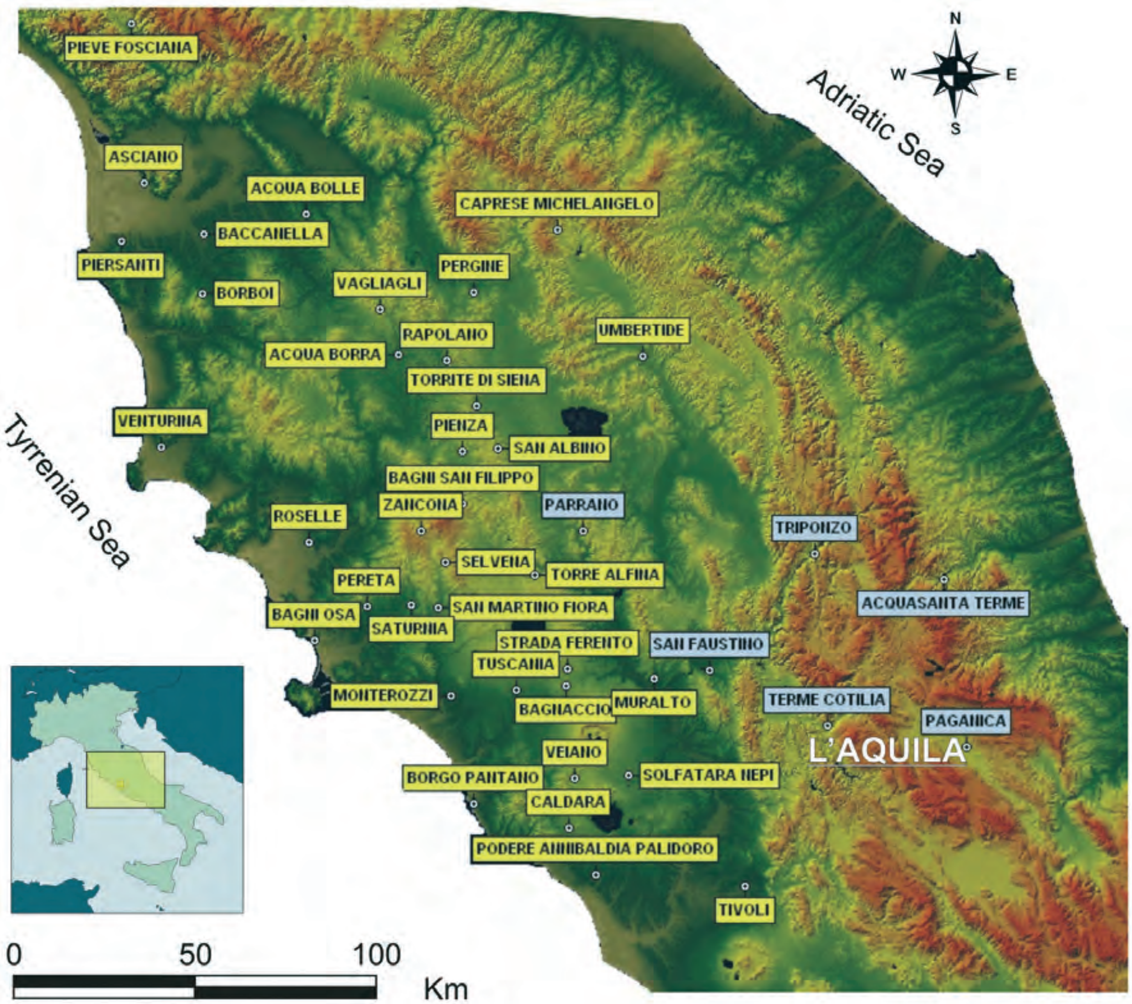

Fig. 1 - Distribution of the main CO_2-dominated vents of central Italy. Table 1 lists the sampling site locations beside the CO_2 and He data. The main seismogenic sources crossing the Apennine chain (after Valensise and Pantosti, 2001) are also reported.

composition and flux could be related to stress-induced strain or to cracks that occurred in deep reservoirs. The peculiar sensitivity of SF gas emission to seismic events and the lack of local sources of man-derived, induced noise led us to choose that site to install instruments aimed at continuous gas flow rate monitoring. The site can be also considered as representative for all the other CO_2-dominated vents spread over the central Apennines characterized by similar geochemical features and sensitivity to crustal deformation and seismicity. Fig. 1 shows the distribution of the well known and already studied vents and thermal springs.

Fig. 2 shows how all samples have a significant increase in CO_2 content with respect to the atmosphere. In particular, samples from the L'Aquila epicentral area (black diamonds) are CO_2-enriched although they were collected from soils and from dry wells, where the air circulation should keep the CO_2 content at, or close to, the atmospheric level. Gas geochemical data and

Table 1 - Sampling site locations with their CO_2 content and their CO_2 and He isotope ratios. The coordinates are given in VTS-WG84 units.

Site #	Site name	Latitude	Longitude	% CO_2	$\delta^{13}CO_2$	R/Ra
1	Pieve Fosciana	4897206	132940	3.3	n.a.	0.06
2	Asciano	4851292	136601	65.6	10.31	0.09
3	Acqua Bolle	4842116	183740	94.8	-6.58	0.02
4	Caprese	4837423	256719	94.8	-4.21	0.03
5	Baccanella	4836167	153970	96.4	-7	0.04
6	Piersanti	4834130	130131	99.1	-6.71	0.14
7	Pergine	4819571	232224	96	-6.93	0.04
8	Borboi	4818901	153440	96	-9.31	0.07
9	Vagliagli	4814551	205176	94.4	-5.18	0.08
10	Acqua Borra	4801192	210303	99.2	-5.95	0.17
11	Umbertide	4800803	281548	92.9	-3.57	0.02
12	Rapolano	4799675	224437	99.3	-7.54	0.13
13	Torrite di Siena	4786346	233189	93.1	-3.87	0.11
14	Venturina	4774391	141376	95.2	-13.4	0.82
15	Pienza	4773372	229191	94.8	-3.69	0.21
16	Bagni S.Filippo	4757952	229238	96.1	-3.33	0.13
17	S.Albino	4751219	244494	96.7	-5.2	0.15
18	Zancona	4750256	217022	94.9	-4.64	0.45
19	Roselle	4746821	184431	27.3	-9.56	0.07
20	Selvena	4740856	224012	90.2	-3.37	0.4
21	Torre Alfina	4737198	250303	98.5	1.01	0.27
22	Saturnia	4728674	214311	34.7	-6.39	0.4
23	Pereta	4728234	201312	75.3	-6.27	0.89
24	S.Martino Fiora	4727675	222162	99.2	0.14	0.69
25	Bagni Osa	4718151	186046	17.7	-9.57	0.09
26	Strada Ferento	4709875	259556	97.9	-0.32	0.56
27	Muralto	4707201	284651	97.3	-0.99	0.64
28	Bagnaccio	4705009	259182	99.3	-1.94	0.54
29	Tuscania	4703754	244956	97.5	n.a.	0.43
30	Monterozzi	4702096	225945	98.4	-0.1	0.36
31	Terme Cotilia	4693510	335135	95.8	-2.1	0.11
32	Solfatara Nepi	4678936	277171	97.6	-1.3	0.26
33	Veiano	4678053	261742	98.3	-0.23	0.45
34	Borgo Pantano	4670899	232195	98	-2.15	0.31
35	Caldara	4663899	260205	98	-2.4	0.24
36	Palidoro	4650026	267870	97.7	-1.88	0.18
37	Tivoli	4647013	311168	91.6	-3.5	0.6

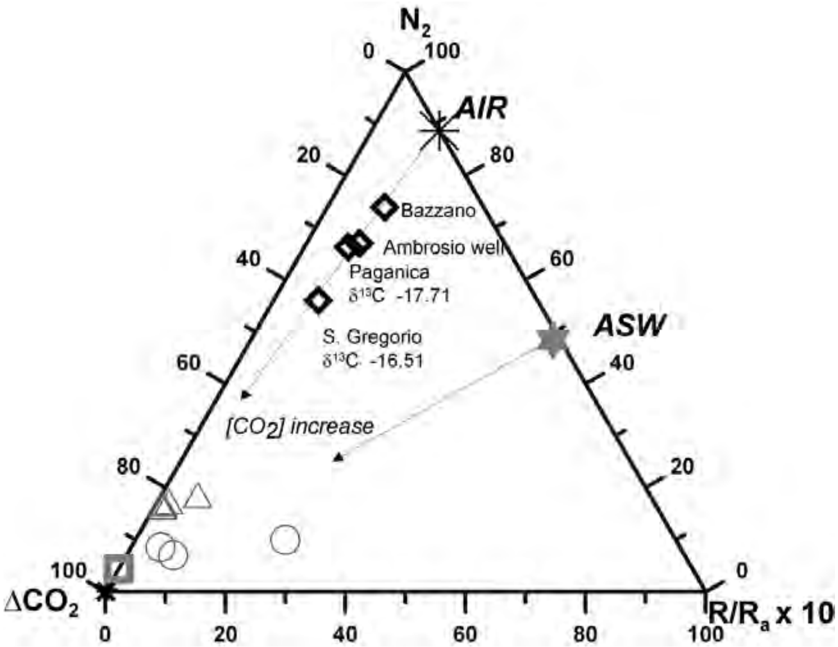

Fig. 2 - R/Ra-N_2-CO_2 triangular plot.

previous literature data (e.g., Chiodini *et al.*, 2004; Minissale, 2004; Italiano *et al.*, 2008) indicate that crustally derived CO_2 is degassed in all of the central Apennines. Gas sampling and soil degassing measurements carried out after the main shock over the L'Aquila area, showed significant CO_2 excess in soil gases (up to 6% by volume) that seems to be related to the seismic sequence. An enhanced CO_2 degassing rate (or even a new, seismically derived, degassing process) is also an indication of deeply-originating gaseous components towards the surface. The CO_2 degassing activity in the L'Aquila epicentral area decreased also the helium isotopic ratio (from the atmospheric ratio R/Ra=1 down to 0.87 R/Ra; Table 2) due to the addition of radiogenic-derived ^4He after the crisis.

The origin of the degassed CO_2 is normally investigated by its $\delta^{13}C$ value, often used to identify the origin of C (e.g., Hoefs, 1980; Schidlowski *et al.*, 1983) as the various CO_2 sources are normally marked by different $\delta^{13}C$ ratios [$\delta^{13}C_{MORB}$ = - 6.5‰; $\delta^{13}C_{Limestones}$ = 0‰; $\delta^{13}C_{Marine\ sediments}$ = -20‰; $\delta^{13}C_{Organic\ matter}$ < -30‰; Faure, (1977), Javoy *et al.* (1986); Sano and Marty (1995)]. Although a contribution of organically-derived CO_2 cannot be excluded, it is worthy of note that the gas samples have been collected from soils during the rainy season and that the CO_2 isotopic ratios of -16.5 and -17.7‰ PDB and even the lowest value detected in soils of -26.42‰ (Table 2) are above typical, organically-derived CO_2. The recorded $\delta^{13}C$ values, however, are consistent with fractionation processes due to gas-water interactions occurring to a gaseous CO_2 that crossed wet sedimentary layers during its uprising toward the Earth's surface, preferentially loosing its heavy isotope (^{13}C).

Both helium and carbon isotopes put in evidence the existence of a CO_2 excess in fluids released over the epicentral area in coincidence with the L'Aquila seismic sequence. Data from a

Table 2 - Analytical results of selected gases sampled in central Italy. Samples from 1 to 7 are free and soil gases collected in the L'Aquila province (Abruzzo region). Sample 8 is a free gas collected in the Rieti province (Latium region). Samples from 9 to 17 are dissolved gases collected in the Perugia province (Umbria region). Sample 18 is a free gas in the Perugia province (Umbria region). The analytical results are expressed as vol. % for free and soil gases and as cc STP/l for dissolved gases. Typical values for AIR and ASW are reported as reference (last two lines, italic characters). Helium isotopic ratios not corrected for atmospheric contamination. * indicates dissolved gases.

Site	N	date	He	O_2	N_2	CO	CH_4	CO_2	$\delta^{13}C$ PDB‰	R/Ra	He/Ne
Paganica	1	16/04/2009	9×10^{-4}	18.6	78.7	4×10^{-4}	0.3×10^{-4}	0.94	-17.71	0.87±0.015	0.36
Paganica Ambrosio well	2	06/05/2009	5×10^{-4}	19.5	78.1	10×10^{-4}	2.4×10^{-4}	0.05	nd	nd	nd
Onna WP071 soil gas	3	06/05/2009	5×10^{-4}	19.1	77.6	6×10^{-4}	2.0×10^{-4}	0.33	nd	nd	nd
WP079 Soil gas	4	08/05/2009	6×10^{-4}	14.2	77.5	10×10^{-4}	1.0×10^{-4}	6.87	-26.42	nd	nd
Bazzano	5	22/07/2009	5×10^{-4}	18.4	79.2	4×10^{-4}	bdl	0.53	nd	1.03±0.047	0.39
San Gregorio	6	22/07/2009	3×10^{-4}	17.8	77.8	29×10^{-4}	1×10^{-4}	1.52	-16.51	1.04±0.054	0.36
Paganica Ambrosio well	7	22/07/2009	5×10^{-4}	18.3	77.6	16×10^{-4}	0.9×10^{-4}	0.84	nd	1.02±0.038	0.33
Cotilia	8	16/04/2009	9.2×10^{-3}	bdl	9.8	1.4×10^{-4}	728×10^{-4}	88.71	nd	0.13±0.006	172.62
Parrano	9	16/04/2009	8.6×10^{-3}	7.6	55.6	0.2×10^{-4}	415×10^{-4}	36.88	nd	0.12±0.006	3.67
Acquasanta*	10	17/04/2009	5.0×10^{-4}	0.02	8.1	6.3×10^{-5}	7.4×10^{-3}	19.79	nd	0.47±0.009	0.83
Acquasanta*	11	27/04/2009	4.0×10^{-4}	0.01	7.2	3.2×10^{-6}	8.0×10^{-3}	21.20	nd	0.81±0.011	0.74
Acquasanta*	12	05/05/2009	2.0×10^{-4}	0.05	4.1	4.7×10^{-5}	2.4×10^{-3}	6.50	nd	1.04±0.059	0.76
Triponzo *	13	17/04/2009	1.1×10^{-3}	0.02	9.5	9.9×10^{-5}	8.9×10^{-2}	11.44	nd	0.08±0.016	5.01
Triponzo *	14	30/04/2009	3.9×10^{-4}	0.02	3.9	1.6×10^{-5}	3.9×10^{-2}	3.86	nd	0.13±0.010	6.80
Triponzo *	15	08/06/2009	1.2×10^{-3}	2.9	8.7	1.7×10^{-4}	8.7×10^{-2}	10.03	nd	0.05±0.004	8.80
Triponzo *	16	26/06/2009	9.7×10^{-4}	0.02	7.4	5.5×10^{-5}	6.4×10^{-2}	8.25	nd	0.08±0.005	4.42
Triponzo *	17	23/07/2009	8.4×10^{-4}	0.02	8.9	bdl	8.6×10^{-2}	10.85	nd	0.07±0.005	5.85
San Faustino	18	06/05/2009	5.0×10^{-4}	0.01	1.3	12×10^{-4}	36×10^{-2}	96.57	0.31	0.26±0.013	68.22
AIR			5.2×10^{-4}	21	78		1×10^{-4}	0.03	-8	1.00	0.32
ASW			4.1×10^{-5}	4.8	9.6		1×10^{-6}	0.24		1.00	0.29

continuous monitoring station installed in the epicentral area after the seismic sequence and still recording data, show dynamic CO_2 concentration constantly above 1%, sometimes up to 3%, that cannot be justified by organic CO_2 production or recycling atmospherically-derived components (Bonfanti, personal communication). Besides the main atmospheric gases circulating over any karst area, an additional gas phase is thus released. As it cannot be of organic origin a deeper, namely crustal, origin for the degassed gases is here considered as shown by the carbon and helium isotopic signatures.

3. Ground based instrumentation methods

CO_2 degassing is a widespread phenomenon for the central Apennines showing significant

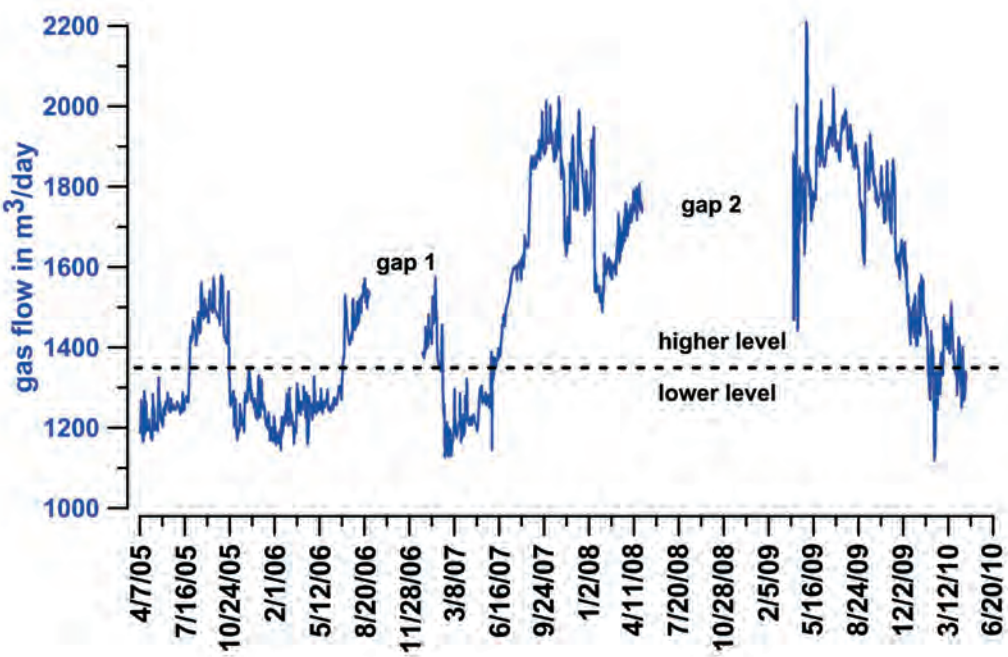

Fig. 3 - The complete gas flow record of SF (blue line). The gas emission was accumulated as gas flow rate per day. Two gaps indicate missing data. The long term observation can be separated into different periods with a higher or lower gas flow level. The interesting short term anomalies of March/April 2009 are in superposition with a high level gas flow rate period in 2009, according to Heinicke *et al.* (2011).

relationships with crustal deformation and seismicity. Both the chemical composition of CO_2-dominated venting and dissolved gases and their flow rate changed in coincidence with seismic events (Italiano *et al*., 2001, 2009b) with a widely increased degassing rate during the 1997-98 seismic crisis (Italiano *et al*., 2001). Both gas vents and thermal springs of the central Apennines release crustal-derived CO_2 with helium marked by a crustal isotopic ratio showing that a deep gas phase of crustal origin is available at shallow crustal levels, sometimes considered as responsible for triggering aftershocks (e.g., Miller *et al*., 2004) also if a small amount of fluids are available at depth (Terakawa *et al*., 2010). An automatic system for CO_2 flow-rate continuous monitoring was installed in a natural vent located at the SF site (Fig. 1). The site was choosen because of the favourable logistic position just beside a factory thus allowing the preservation of the site. The gas flow was measured in a plastic pipe of 30 cm in diameter for a free gas outlet. A thermo couple "hot wire" type sensor (Schmidt Company®) recorded the gas velocity which is then converted into flow rate. Fig. 3 shows the complete records of the period 2005-2010 with two gaps in 2006 and 2008-2009. The evaluation of the gas flow variation shows long term periods with higher or lower gas flow levels. Heinicke *et al*. (2011) interpret the long term variations with pore pressure perturbations in the crustal reservoirs induced by static stain variations. Local seismic events, as expression of geodynamic processes in the near field, always occurred before and during these anomalous gas flow periods. This correlation exists only for events that occurred east of the gas emission site close to the local major fault zone, the Martana

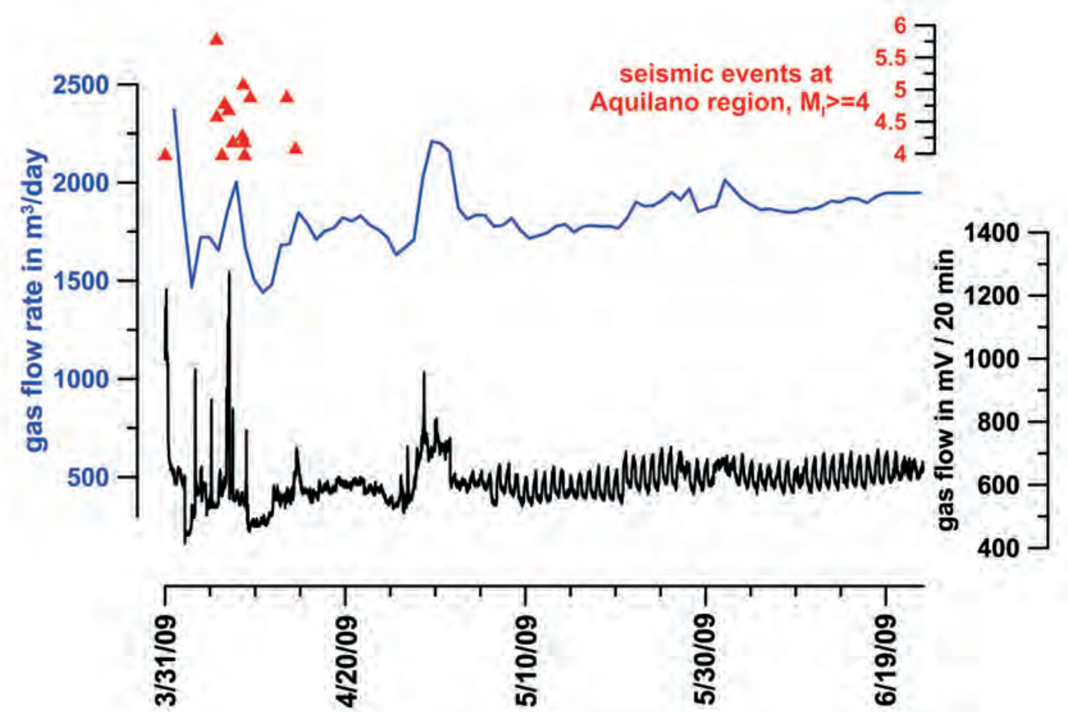

Fig. 4 - Gas flow records at SF: the original record of 20 minute interval (black line) and the accumulated daily gas emission rate (blue line). The contemporary seismic activity of the strongest events at the Aquilano region is marked by red triangles. Anomalous gas emissions with short term characteristics can be recognized at the beginning of the crisis, according to Heinicke *et al.* (2011).

fault zone. We herein consider this correlation as indication for a continuous interaction between the field of static strain and the deep fluid pressure and their transport paths.

The records of 2009 are of particular interest if we consider their possible interaction with the static strain accumulation before the L´Aquila seismic crisis. After a period of malfunctioning, the station was restored and the monitoring started again on March 31, 2009, seven days before the main shock of the seismic sequence that occurred in the Abruzzo region. The seismic sequence was characterized by thirteen events larger than magnitude 4 and by the M_w= 6.3 (M_L = 5.9) main event on April 6. During the monitoring period strong variations in the gas flow rate were observed (Fig. 4). In particular, sharp variations were observed during the first two weeks while a long term decreasing trend was observed in the following months (Fig. 3). These anomalies are different in their duration (a few hours up to some days) and their intensity (about 50-100% increased flow rate) in comparison to the long-term variations.

These short term fluid emissions can be influenced by meteoclimatic factors and by geodynamic processes which affect the crustal stress field (Manga and Wang, 2007). Once excluded or eliminated by a data set, all possible meteoclimatic noise sources, possibly geodynamically-originated signal sources can be further investigated. The recorded data in 2009-2010 are plotted in Fig. 5, showing the daily gas flow and the meteoclimatic parameters (temperature, barometric pressure, rain and wind speed). Possible interactions with the

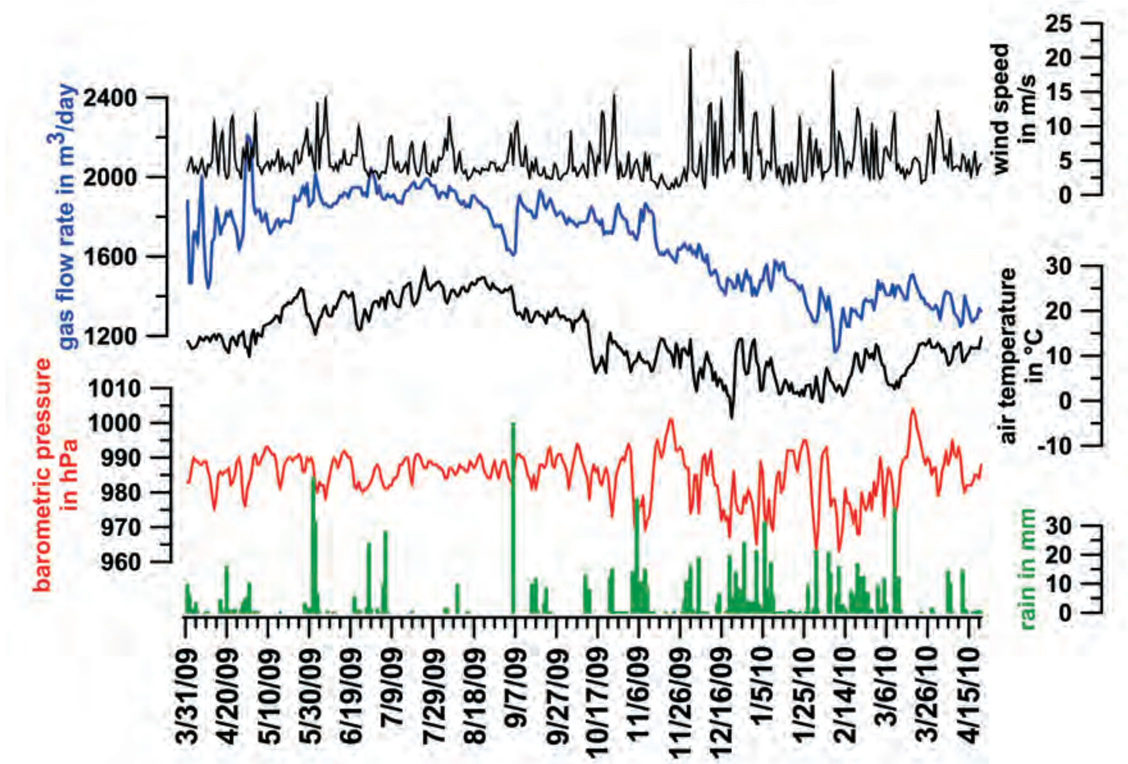

Fig. 5 - One year of daily gas flow rate (blue line), wind speed (upper black line) air temperature (lower black line), barometric pressure (red line) and rain (green bars) at SF, starting on March 31, 2009.

meteoclimatic parameters as cause of the fluctuations of gas flow data has to be analyzed first. The meteoclimatic factors can be removed from the daily gas flow time series by using the singular spectrum analysis (Vautard *et al*., 1992), which provides a decomposition of short and apparently noisy signals. The daily gas flow is decomposed into 180 components R_i. Each component R_i is cross-correlated with one meteoclimatic variable, and the maximum of the cross-correlation function is compared with the 95% confidence level, assuming that the two series are completely uncorrelated. If such maximum is higher than the confidence level, the corresponding component R_i is removed from the gas signal. Figs. 6 and 7 show the maximum of the cross-correlation between each component R_i and the meteoclimatic variables (temperature, pressure, rain and wind speed, respectively) along with the 95% confidence level. All the components of the gas flow whose maximal cross-correlation is higher than the confidence level are removed from the gas flow.

The gas flow thus filtered is investigated for the existence of strong periodicities, mainly linked with the Earth's tides. Fig. 8 shows the periodogram obtained, which reveals a strong periodicity at about 27.57 days, very probably linked to the Earth's lunar tide.

After removing the main periodicity, the residual gas flow is plotted in Fig. 9 along with the earthquakes that occurred during the observation period and the 2σ threshold to identify the gas flow anomalies. In Fig. 10≠, the residual gas flow in the first 70 days of measurement is shown

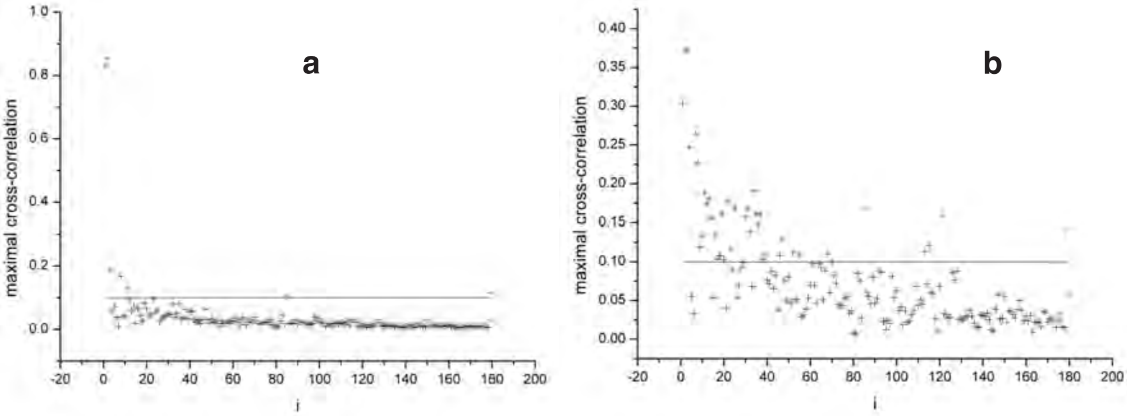

Fig. 6 - Maximal cross-correlation between temperature (a) and pressure(b) and the component R_i of the gas flow. The horizontal line indicates a 95% confidence level.

together with earthquakes occurring in the same period.

The monitoring of gaseous fluid emission in SF 2009 shows significant anomalies in concomitance with the L'Aquila seismic swarm. Gas flow fluctuations cannot be explained by meteorological or man-induced factors thus they are geogen. The long term anomalies in the past years can be explained as the result of slow crustal deformative processes which affect the local reservoirs and transport paths in the near field. The short term anomalies at SF at the beginning of April should be considered as evidence of a disturbed fluid transport system in the upper horizons or of trapped gas pockets likely triggered by the L`Aquila swarm onset. Other seismic activity does not occur in the near field. The coincidence of the strong events with the first occurrence of these anomalous fluctuations (end of March) in a distance of about 80 km and their

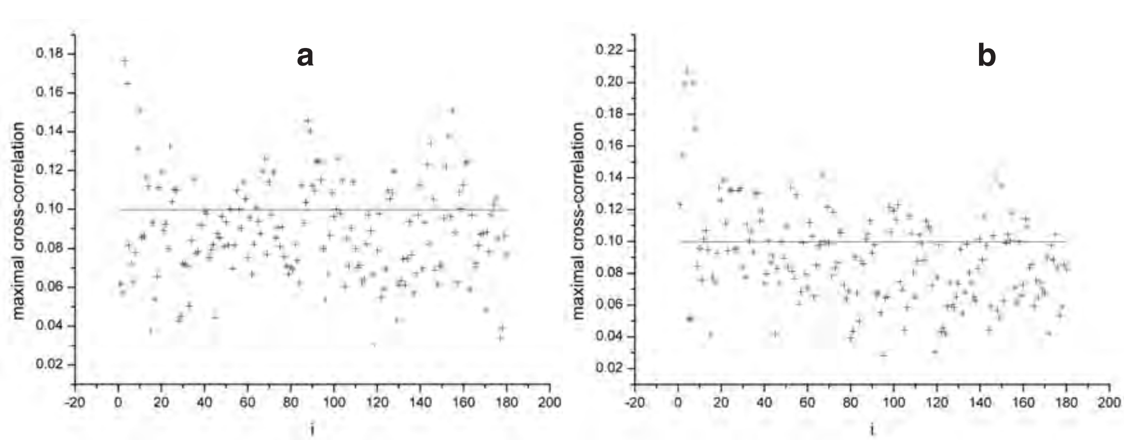

Fig. 7 - Maximal cross-correlation between rain (a) and wind (b) and the component R_i of the gas flow. The horizontal line indicates a 95% confidence level.

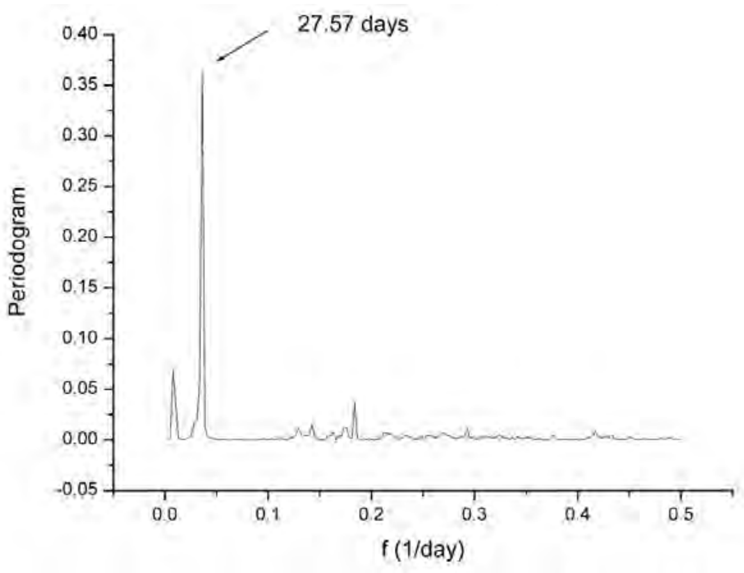

Fig. 8 - Periodogram of the gas flow after removing the components, that were correlated with the meteoclimatic variables. The strongest periodicity is at about 27.57 days.

disappearance at the end of April suggest a dynamic, strain-induced, trigger mechanism of anomalous generation in the far field. Improved fluid transport conditions by increased diffusivity or crack propagation can be also discussed. A higher hydraulic diffusion coefficient of several hundred m^2/s would imply the possibility of the transmission of pressure gradients along the NW-trending fluid system to the SF site over a period of several weeks or months. In a similar case, Antonioli *et al*. (2005) estimated a fault-specific anisotropic diffusivity in the range of D_{aniso}= 250 m^2/s according to the analysis during the seismic crisis of Umbria-Marche 1997.

As a general remark, supposing the SF gas vent is representative of the behaviour of other CO_2 vents of the central Apennines, as already recorded during the Umbria seismic crisis (Italiano *et al*., 2001), an enhanced degassing rate is postulated for the whole area. On the other hand, although no investigation had been carried out on the main gas vents located over the Umbria region, an increased amount of dissolved CO_2 was recorded at the thermal springs of Triponzo and Acquasanta Terme, respectively, located in the Umbria and Marche regions. An automatic device to measure continuous soil degassing was installed close to the town of L'Aquila in November 2009, seven months after the mainshock, showing that a CO_2 degassing was and still is detectable with some seasonal changes (Bonfanti, personal communication) that are similar to those recorded over the same time span at the SF site.

4. Satellite data analysis: the RST approach

The RST method identifies signal anomalies in the space–time domain as deviations from a normal state that has been preliminarily identified on the basis of satellite observations collected over several years, under similar observational conditions for each image pixel and period of the year. For earthquake-prone areas monitoring, anomalous TIR patterns are identified by using a specific index, RETIRA [Robust Estimator of TIR Anomalies; Filizzola *et al*. (2004), Tramutoli

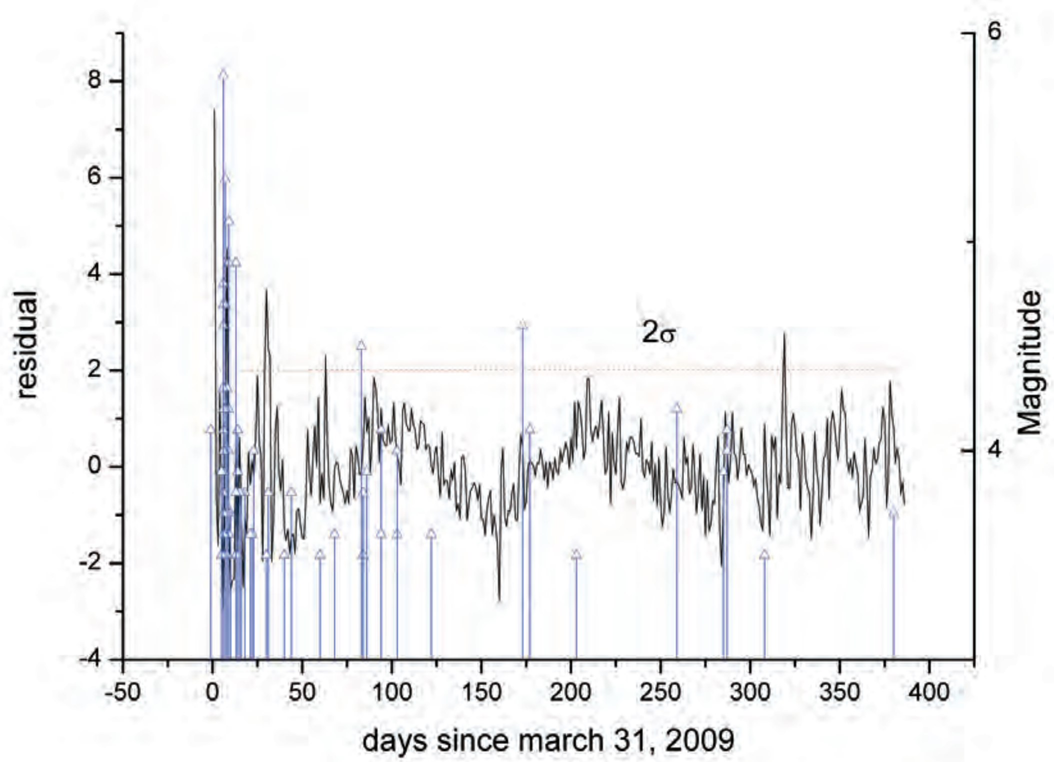

Fig. 9 - Residual gas flow after removing the meteoclimatic effects and the periodicity shown in Fig. 8. The vertical blue arrows indicate the earthquakes that occurred within a radius of 100 km and characterized by $M \geq 3.5$ during the period of recording. The horizontal, dotted red line indicates the 2σ threshold for the identification of anomalies in the residual gas flow.

et al. (2005)] to be computed on the image at hand as in the equation below:

$$\otimes_{\Delta T}(\mathbf{r},t) = \frac{\Delta T(\mathbf{r},t) - \mu_{\Delta T}(\mathbf{r})}{\sigma_{\Delta T}(\mathbf{r})}$$

where:

$\Delta T(\mathbf{r},t)=T(\mathbf{r},t)-T(t)$, $T(\mathbf{r},t)$ is the punctual value of the brightness temperature at the location $\mathbf{r}\equiv(\mathbf{x},y)$ and acquisition time *t;*

$T(t)$ is the spatial average computed in place on the image at hand considering cloud-free pixels only, all belonging to the same, land or sea, class in the investigated area IA (i.e., $T(t)$ is computed considering only sea pixels if **r** is located on the sea and computed considering only land pixels if **r** is located on the land). Note that the choice of such a differential variable $\Delta T(\mathbf{r},t)$ instead of $T(\mathbf{r},t)$ is expected to reduce possible contributions (e.g., occasional warming) due to day-to-day and/or year-to-year climatological changes and/or seasonal time-drifts;

$\mu_{\Delta T}(\mathbf{r})$ and $\sigma_{\Delta T}(\mathbf{r})$ are the time average and standard deviation of $\Delta T(\mathbf{r},t)$ obtained for each

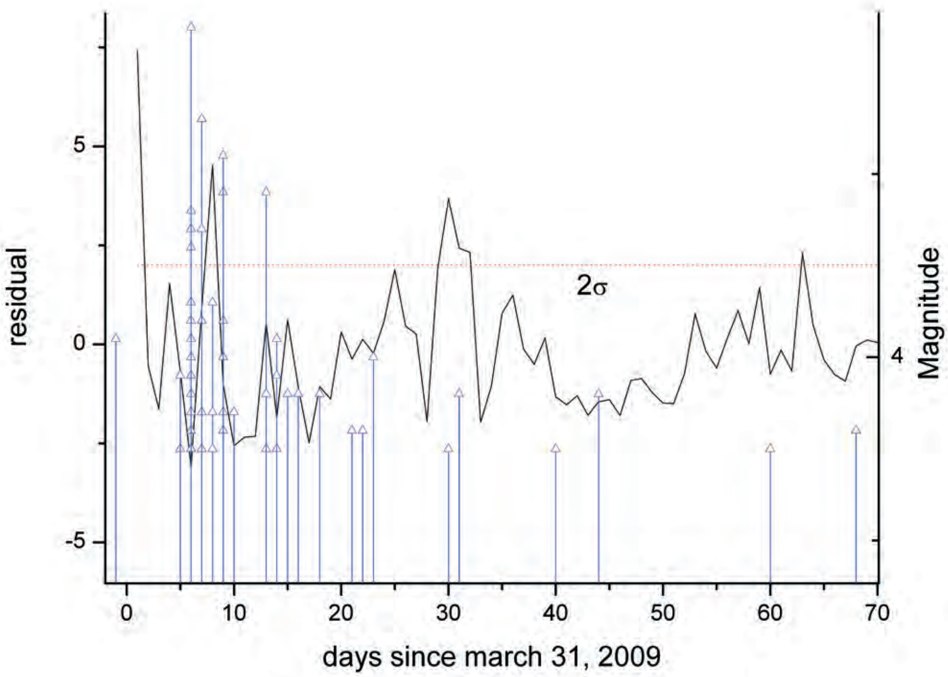

Fig. 10 - Residual gas flow after removing the meteoclimatic effects and the periodicity shown in Fig. 8 during the first 70 days of recording. The vertical blue arrows indicate the earthquakes that occurred within a radius of 100 km and characterized by $M \geq 3.5$ during the period of recording. The horizontal dotted red line indicates the 2σ threshold for the identification of anomalies in the residual gas flow.

location **r**≡(**x**,*y*) using cloud free records belonging to a homogeneous data set of observations collected in different years in similar (same month, same time of the day, etc.) observational conditions.

5. Satellite data evaluation

For this study, the RST approach has been implemented on MSG-SEVIRI (Meteosat Second Generation -Spinning Enhanced Visible and Infrared Imager) data. Five years (from 2005 to 2009) of SEVIRI TIR (channel 9 at 10.8 micron) images acquired at the same time of day (24:00 GMT) during the months of March and April were used to characterize the expected signal behavior in unperturbed conditions. The geographic corners of the investigated area (IA) covering the whole of Italy, were 35°N; 6°E and 48°N; 19°E. On this basis the RETIRA index has been computed for all the MSG-SEVIRI imagery in order to perform the validation/confutation analysis. For validation purposes, the months of March and April 2009 have been considered, while, in the confutation phase, the analysis has been performed considering the months of March and April 2008: the "unperturbed" (i.e., no earthquakes with $M \geq 5$, in the same region and in the same months but in a different year) period in the considered data set. SEVIRI records

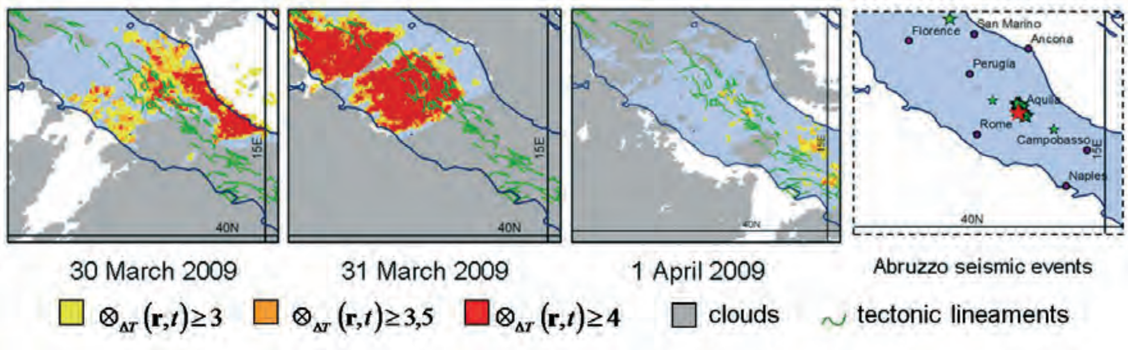

Fig. 11 - Validation analysis. SEVIRI images at 00:00 GMT having pixels with RETIRA>4 are reported at a different level of intensity.

corresponding to cloudy affected radiances have been identified by using OCA [One-channel Cloudy-radiance-detection Approach: Tramutoli *et al*. (2000), Pietrapertosa *et al*. (2001), Cuomo *et al*. (2004)] and excluded from whatever subsequent processing.

For validation purposes the RETIRA index [$\otimes_{\Delta T}$ ($\mathbf{r}$,t)] has been computed for all available midnight images in the months of March and April 2009. A persistence analysis (Tramutoli *et al*., 2005) has been performed in order to discern significant (i.e., space–time persistent) anomalous TIR transients from outliers, possibly due to image navigation errors or to night-time cloud passages [described by Filizzola *et al*. (2004)] or to the well known cold spatial average effect due to a southern dominant cloud distribution across the scene already described by Aliano *et al*. (2008a) and in Genzano *et al*. (2009a). In this way significant TIR anomalies have been identified in a wide area over the Abruzzo region from March 30, 7 days before the main shock of the Abruzzo earthquake and a few hours before its strongest foreshock (M_L~4.1) that occurred at 13:38 UTC on April 1. Similar results [with obvious limitations from the use of polar satellites described in Filizzola *et al*. (2004)] were reported by Lisi *et al*. (2010) and Pergola *et al*. (2010), applying the same RST approach on NOAA/AVHRR and EOS/MODIS TIR data. In Fig. 11, TIR anomalies with a different level of intensity of RETIRA index are reported.

The confutation step was performed by considering the same period (March 15- April 15) but in a different year (2008), in order to verify the absence of TIR anomalies in a relatively seismically unperturbed period (see Genzano *et al*., 2009a). It is possible to note that just one sequence of TIR anomalies appear in the period considered (Fig. 12). From March 16 to 20 space-time persistent TIR anomalies appear in southern Italy (Calabria region). A seismic event with magnitude M_L~4.0 occurred in the same area on April 8, 2008. Other anomalies appear as spatially isolated and/or not time persistent (disappearing just in one day) probably related to night-time cloud passages and/or errors in image navigation/co-location processes (see Filizzola *et al*. 2004; Aliano *et al*. 2008a).

During the L'Aquila seismic sequence local crustal deformations were monitored by laser strain meters (Amoruso and Crescentini, 2010), by DInSAR satellite interferometry (Anzidei *et al*., 2009) and by GPS stations Anzidei *et al*. (2009). No significant pre-seismic signal was

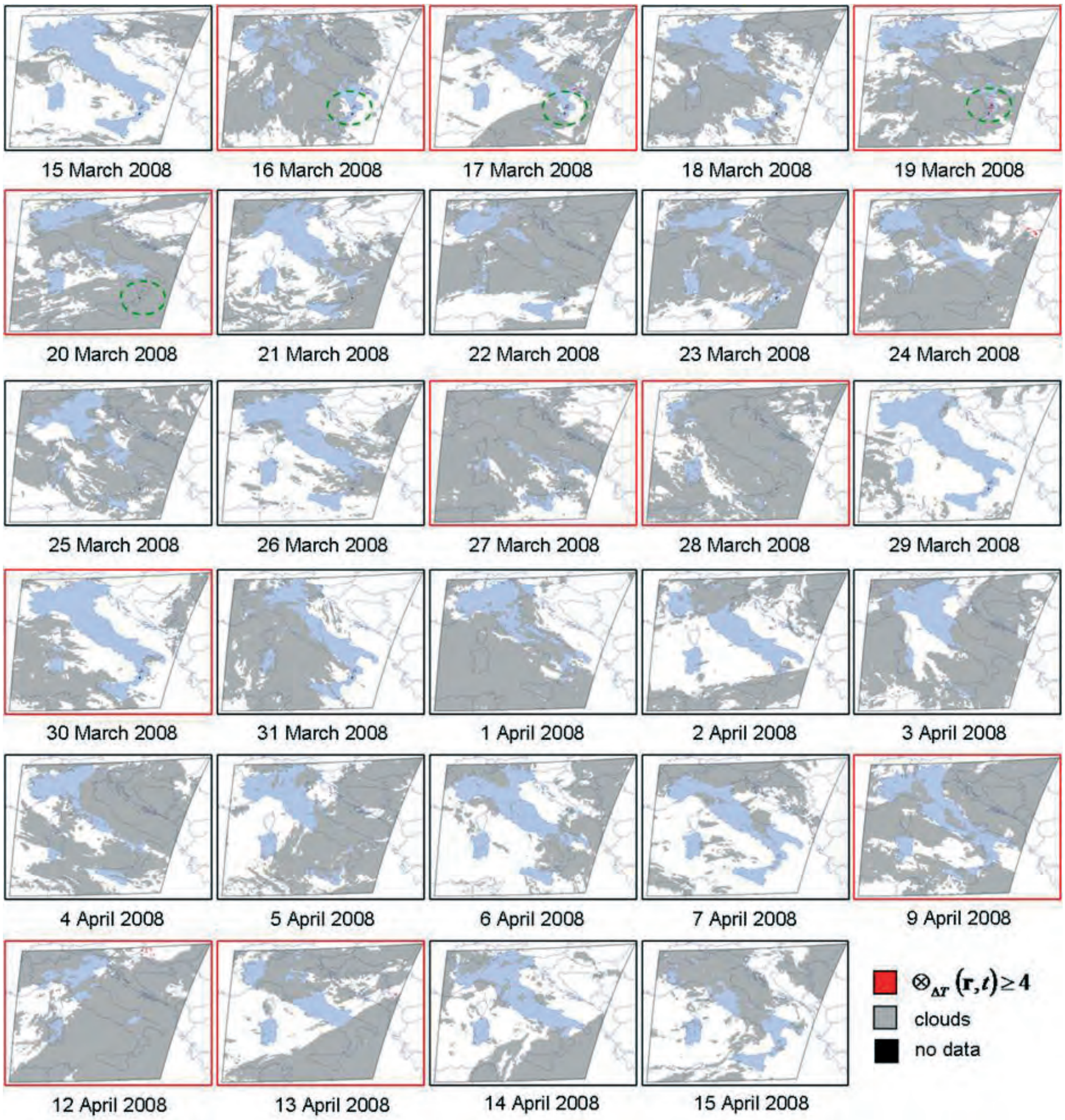

Fig. 12 - Confutation: results of the RETIRA index computation over the investigated area for the relatively unperturbed year 2008. Red boxes contour images having pixels with retira index ≥ 4. Green circles indicate the (unique) sequence of space-time persistent TIR anomalies over the Calabria region.

detected, probably due to the limited areal significance of laser strain meters and to the lack of a pre-main shock DInSAR data. No significant pre-main shock GPS possible anomalous data were detected by GPS data by Anzidei *et al*. (2009) probably due to the reduced resolving power of the monitoring network. Caporali (2009) recorded significant anomalous GPS signals starting at the end of March 2009 but no definitive conclusion has yet been published about possible crustal topographic anomalous deformations before the mainshock of the L'Aquila seismic sequence. On the other hand, an eventual deformative pattern could be difficult to detect by means of the available instruments. Di Luccio *et al*. (2010) and Plastino *et al*. (2010) detected pre-seismic, fluid-related signals consistent with strain occurrence at depth, probably not easily detectable at ground surface. Ground-based and satellite-based, deep originated, gas monitoring data are consistent with increased crustal permeability probably induced by strain processes at depth and significant signals were detected some days before the mainshock.

6. Conclusions

The one-year monitoring of gaseous fluid emission in SF shows significant anomalies in concomitance with the L'Aquila seismic swarm. During the most intense phase of gaseous outflow, large scale TIR anomalies were detected from 7 days before the main shock by applying RST data analysis to MSG/SEVIRI data. Similar results were independently achieved by Lisi *et al*. (2010) and Pergola *et al*. (2010) by applying the same RST approach on TIR data acquired from different (NOAA/AVHRR and EOS/MODIS) satellite sensors. No similar significant TIR anomalies have been detected from satellite observations in the seismically unperturbed periods (March-April 2008) considered for confutation purposes. It should be noted that the most intense and extended TIR anomalies observed from the satellite, appearing in the epicentral area only a few hours before the main foreshock (M_L=4.1 on March 31), are observed in coincidence with significant variations of different geophysical parameters independently reported by several authors.

In addition to the ones (Caporali 2009; Lisi *et al*., 2010; Pergola *et al*., 2010) already quoted above, having their maximum exactly in the same day (March 31), other anomalous variations of different geophysical parameters, refering to the same period, are independently reported [e.g., Rozhnoi *et al*. (2009) who report significant anomalies in VLF records starting 2 weeks before the main shock with a last relative maximum on March 31]. Always in the same period, further fluid-related anomalies were detected by Plastino *et al*. (2010) who observed geochemical variations in underground waters and by Di Luccio *et al*. (2010) who reported significant variations in V_p/V_s ratios. The V_p/V_s seismological observations that Lucente *et al*. (2010) report seem particularly important. The explanatory model (progressive emptying of a wide gas reservoir triggered by the event of March 31) fits perfectly with the one already proposed by Tramutoli *et al*. (2001, 2005) correlating TIR anomalies with an abrupt increase of green-house gas emissions.

The gas geochemistry shows how a CO_2-dominated gas phase has been degassed through the ruptures occurring in the epicentral area. Such a phenomenon was also recognized in the main aquifers of the area (Chiodini *et al*., 2011) and involved a much wider area than the epicentral (Italiano *et al*., 2009a) one. In order to verify the possible relation between anomalous gas release and crustal deformative processes (Atzori *et al*., 2009) due to the L'Aquila seismic sequence, a statistical data analysis (able to exclude the possible role of meteoclimatic factors) has been carried out on a long term series of measurements of gas emission performed at the SF site in the epicentral area.

The analysis demonstrated that gas-flow fluctuations cannot be explained by meteorological or man-induced factors, so that spike-like and long term anomalies can be explained as the result of crustal deformative processes and/or crack openings accompanying the L'Aquila seismic swarm. Anomalous signals recorded some days before mainshock evidence showed that crustal deformative processes and/or crack openings started some days before the mainshock.

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