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The first observations of CO_2 and CO_2/SO_2 degassing variations recorded at Mt. Etna during the 2018 eruptions followed by three strong earthquakes

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ABSTRACT

Mount Etna volcano is well-known for its frequent eruptions and high degassing rates from its summit craters and flanks. The geochemical monitoring network on Mt. Etna that measures soil CO_2 flux and in-plume CO_2/SO_2 ratio recorded very important degassing variations from the flank and the summit craters during the second half of 2018. In this area several significant volcanic events occurred in October and December 2018 and in January 2019. Past observations have distinguished a tendency for wide variations in degassing rates, marked by a sharp increase preceding the onset of volcanic activity. However, this is the first time that three earthquakes of magnitude M>4 have been registered since the inception of the geochemical network in January 2001. Of particular interest is the CO_2/SO_2 ratio in plumes recorded by the monitoring station sited at the summit crater of Voragine showed very significant degassing variations, which were comparable with those recorded for the soil CO_2 flux.

This paper focuses on the combination of events occurring on Mt. Etna and their relationship with degassing rates. The most remarkable results can be summarized as follow: i) the networks recorded high variations of soil CO_2 flux and CO_2/SO_2 ratio, which assisted in identifying distinctive phases of pressurization of Mt. Etna plumbing system and ii) all earthquakes occurred during phases of minimum gas rate, which in turn followed stages of pressurization involving different portions of the plumbing system. The 2018 period of high volcanic activity and the corresponding seismic episodes provided an invaluable case study for Mt. Etna, which allowed to combine seismic events and geochemical signal variations.

Key Words: *soil CO_2 flux, CO_2/SO_2 plume ratio, Etna volcano, volcano monitoring, volcanic degassing.*

INTRODUCTION

Carbon dioxide degassing in volcanic areas has important implications in: i) monitoring volcanic activities (Gurrieri & Valenza, 1988; Chiodini *et alii*, 1998; Hernandez *et alii*., 2000; Liuzzo *et alii*, 2013; Viveiros *et alii*, 2014; Boudoire *et alii*, 2017a); ii) studing tectonic structures (Giammanco *et alii*, 1998, 2006; Hernandez *et alii*, 1998; Liuzzo *et alii*, 2015; Boudoire *et alii*, 2017b), and iii) understanding magma dynamics and plumbing systems as a whole (Chiodini *et alii*, 1998). CO_2 release depends on various characteristics such as: i) high abundance of undegassed magma; ii) solubility of CO_2 in melt, which decreases as the pressure reduces during ascent to the surface; and iii) tectonic structures through which the gas is released. Consequently, over the years several studies have been performed in active volcanic areas in time and space with the aim of clarifying the relationships between degassing and volcano-tectonic activity, developing new methods of measuring flow and content of CO_2 (Finizola *et alii*, 2002, 2004, 2009; Lewiki *et alii*, 2003a, 2003b), and developing new models to filter signals (Viveiros *et alii*, 2008; Boudoire *et alii*, 2017a, 2017b) affected by meteorological effects and/or interactions with rocks and aquifers during ascent.

Located in the middle of the Mediterranean Sea, Mt. Etna is one of the most studied active, basaltic volcanoes in the world (Fig. 1). It is famous for its frequent eruptions and diversity of eruptive dynamics: lava flows, lava fountains and ash emissions, all from the summit craters and new eruptive vents and fissures, which periodically open on the flanks of the volcanic edifice. In the last decades, these phenomena have almost continuously occurred with paroxysms of various intensity and type, alternating with short periods of inactivity. These facts imply that Mt. Etna is a powerful natural laboratory to test models, instruments and processing algorithms for research and civil protection purposes. The Istituto Nazionale di Geofisica and Vulcanologia (INGV) has developed an automatic network for the measurement of the CO_2 flux diffusing through the soil (ETNAGAS network) and a new model to filter meterorological influences from the data (Liuzzo *et alii*, 2013) .

This paper presents and discusses new data acquired from the ETNAGAS network between January 2018 and February 2019. This period was characterized by strong volcanic activity, concurrent with various seismic events characterized by magnitudes M >4 (the highest recorded magnitude since the geochemical network was deployed in January 2011 in its present configuration) and strong variation in soil CO_2 emissions. Significant variations in the rate of volcanic degassing were observed prior to the onset of the 2018 eruptive period, clearly indicating a new input of deep rich-CO_2 magma feeding the intermediate plumbing system of Mt. Etna. In addition, a consistent trend of CO_2/SO_2 ratio in the plume gases was recorded by the monitoring station sited on the rim of the Voragine crater, thereby confirming the overall trend of the volcanic degassing path in this specific period. The three main M >4 seismic events occurred during a relative minimum of degassing. The aim of this paper is to highlight the relationships between the seismic and volcanic activities occurring during the period October to January 2019.

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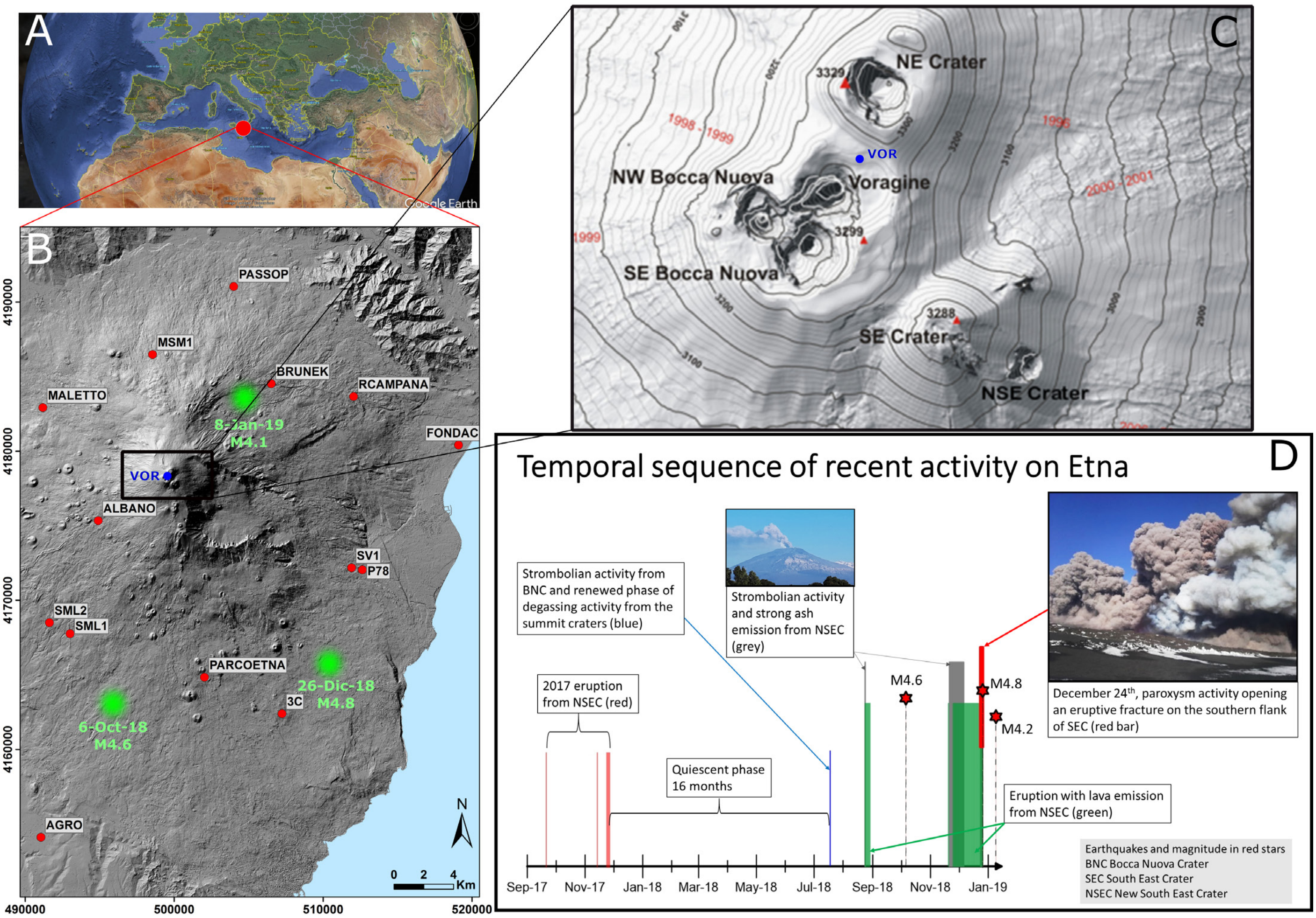

Fig. 1 - A) Location of Mt. Etna volcano. B) Red circles indicate the sites of the soil CO_2 monitoring stations of the Mt. Etna gas network; blue circle indicates the location of the MultiGAS monitoring station sited on the northern rim of Voragine crater; green circles denote the epicentres of the seismic events discussed in the text. C) Summit area of Mt. Etna with the locations of the main craters. D) Temporal sequence of the Mt. Etna activities discussed in the text.

THE ETNA GEOC HEMICAL NETWORKS

The ETNAGAS network and the CO_2/SO_2 station for the monitoring of the volcanic plume was developed by the INGV laboratories of Palermo. The hardware of the soil CO_2 stations is based on the measurement method proposed by Gurrieri & Valenza (1988), and it consists of a probe, which permits the gas to be pumped from the ground by mixing it with air. The dilution ratio depends mainly on three factors: (a) the geometry of the probe; (b) the depth of insertion of the probe into the ground; and (c) the suction flow of the gases, mixed inside the probe (Gurrieri & Valenza, 1988). The CO_2 concentration value obtained with this method is proportional to the CO_2 flux released from the ground. The method was calibrated in the laboratory using a soil sample, which was exposed to CO_2 flux under controlled conditions. The equation, originally proposed by the authors, was subsequently modified (Camarda *et alii.* 2006) to introduce soil permeability, a parameter which influences the measurement and, therefore, the calculated CO_2 flux.

The network consists of 14 stations (Fig. 1) located on Mt. Etna at altitudes between 600-1,700 m asl. Data, including CO_2 flux, atmospheric temperature, pressure and water content, rain, wind speed and wind direction are acquired hourly. The data are processed every day at INGV Palermo and used for research and the evaluation of the volcanic activity for civil defence goals.

The acquisition of the CO_2/SO_2 data in-plume is provided by the MultiGAS instrument (Aiuppa *et* al; 2008 and reference therein), which was entirely designed and built at the INGV laboratories. The MultiGAS is equipped with an NDIR spectrophotometer for detecting CO_2 concentrations (Gascard Edinburgh Sensors) in the range of 0-3000 ppm/v, and an electrochemical sensor for SO_2 (City Technology Ltd.) with a range of 0-100 ppm/v. The station is located at the summit of Mt. Etna on the rim of the Voragine crater. The station acquires gas concentrations over a perior of 30 min, four times per day. Gas temperature and relative humidity are also monitored in order to calculate the H_2O amount by the Arden Buck equation (1981). In recent years, CO_2/SO_2 variations have regularly correlated with volcanic activity, thereby revealing consistent indications with the ascent of a degassing, CO_2-rich magma prior to eruption episodes (Aiuppa *et alii*, 2007, 2010)

VOLCANIC AND SEISMIC ACTIVITY ON MOUNT ETNA

In the following, a summary of the main volcanic and seismic events, which occurred between September 2017 and February 2019 on Mt. Etna, is reported. This information was extracted from the INGV Catania Section reports regarding the volcanic and seismic activity occurring in this area.

Mt. Etna was characterized by a period of quiescence from January to mid-July 2018, as shown in Figura 1. The first signals of a resurgence of volcanic activity occurred in mid-July, when the Bocca Nuova crater (BNC) showed explosive activity with emissions of fragments of magma outside the crater. BNC is one of the three summit craters typically characterized by explosive behaviour (Cannata *et alii* 2015), hitherto inactive since 2013. The reactivation of the volcanic activity after a quiescent period of 16 months occurred with no significant changes in terms of volcanic tremor, with the tremor source located below the summit craters at a depth of 3,000 m.

After the mid-August 2018, Strombolian activity increased appreciably, affecting the North-East crater (NE) and the New South-East crater (NSEC). The activity produced ejections of coarse material emanating from the crater rims and emissions of lava with a casting towards the Valle del Bove. In the following days, the volcanic tremor increased and new overflows of lava from the NSEC were observed up to August 25, 2018 when the activity decreased and ceased at the end of August, even if mild Strombolian activity continued.

On September 5, 2018 Strombolian activity increased again, accompanied by explosions at the NSEC, ash emissions and seismic energy release. The strongest of these explosions was felt by the population in the eastern sector of Mt. Etna. Thereafter, the Strombolian activity progressively decreased until September 13, 2018 when a new main explosion occurred during which ash emission were observed.

On October 6, 2018 at 00:34 a.m. (UTC) an unusually strong earthquake of M=4.6 occurred at a depth of approximately 9 km bsl and located 2 km south of Ragalna (Catania). This seismic event occurred with no evident of volcanic activity at the top vents (Fig. 1). With exception of this event, the mid-September-mid-October 2018 period displayed no significant activity until the afternoon of November 20, 2018 when a modest and discontinuous lava flow occurred.

On December 6, 2018, the lava emission became constant and the frequency of explosions increased at the NSEC, BN and NE craters. This activity remained fairly constant until December 24, 2018 when a new, strong increase in several monitored parameters indicated rapid growth of the volcanic activity on Mt. Etna. The observations included : a) strong increase of volcanic tremor; b) seismic swarms with main shocks below the crater area and below Valle del Bove; c) ground deformation at the top of the volcano; d) intense Strombolian activity from a new fissure, which opened on the south flank of the NSEC and ash emissions. A new eruptive fissure on the east flank of the NSEC at 3,000 m asl was also observed from where persistent Strombolian activity was recorded. These variations occurred prior to a new seismic event (M=4.8) on December 26, 2018 located 1.1km south of Lavinaio at a depth of 1.2 km. The day after this second event, the lava flow from the new fracture progressively decreased and eventually ceased.

No significant volcanic activity was recorded in early January 2019. The most important event occurred on January 9, 2019, with a new seismic event (M=4.1) located 1.8 km west from I Due Monti at a depth of 2.2 km. This event was followed by appreciable Strombolian activity. On January 23 2019, ash emissions were observed from the NE crater which reached the town of Giarre. Strombolian activity and ash emissions continued with variable intensity until the end of February 2019, and for the next three months there was no appreciable volcanic activity in this area. It is of note that the earthquake occurring at the beginning of October 2018 was significantly deeper than those observed at the end of 2018 and early 2019.

DATA PROCESSING

Soil CO_2 degassing signals can be influenced by meteorological variations (Viveiros *et alii*, 2008; Liuzzo *et alii*, 2013; Boudoire *et alii*, 2017a). Therefore, before investigating the relationships between soil degassing variations and volcano-tectonic activities, it was necessary to filter signals from these meteorological influences. The frequency of recorded data was adjusted from hourly values to daily averages and spikes, resulting from instrument noise, removed. Variations due to temperature, pressure and wind were also removed. Moreover, data losses, up to a maximum of three days, were compensated by linear interpolation (i.e., three data points).

Two different methods were applied to filter the meteorological influences: the OVPF method, developed by the Observatoire Volcanologique du Piton de la Fournaise, used on La Réunion island (France); and the MAFILT method, developed by the INGV Palermo (Italy), which is used to filter the data acquired on Mt. Etna (Table 1).

The OVPF method has been used since 2013 to process data acquired by the soil CO_2 gas network on Piton de la Fournaise volcano, a monitoring system based on the same technologies as the INGV network (Boudoire *et alii*, 2017a). This method consists of subtracting the components caused by atmospheric variations from the original signal through single and/or multiple linear regression with atmospheric temperature and pressure. This significantly reduces the correlation between the signal of soil CO_2 degassing and the meteorological parameters (R^2<0.1). This procedure was applied to eight out of 13 stations where a strong dependence on the atmospheric temperature was initially observed. After this initial step, the remaining seasonal components were identified by Fast Fourier Analysis. A common yearly periodicity was observed on nine out of 12 stations and removed by filtering for the 300-450 day period (Liuzzo *et alii*, 2013; Boudoire *et alii*, 2017a).

The "MAFILT" (Moving Average FILTer) is automatically applied to the data recorded by the ETNAGAS network. It is based on the moving averages of the CO_2 flux signals, acquired by 14 monitoring stations. The filtering process can be summarized as follows: i) data acquired from each station were averaged daily and filtered by a low pass 30-day moving average. This new data-series (referred to as High Frequency Filterd, HFF) did not reveal components with period shorter than one month; ii) the HFF series was processed with a 390-day moving average filter to extract the Long Period cyclic Trend (LPT, which contained signal variations with period longer than one year); iii)

TABLE 1

Comparison between filtered signals of soil CO_2 flux using (1) the OVPF method (Boudoire *et alii*, 2017a) and (2) the MAFILT method (Liuzzo *et alii*, 2013) for the period January 1, 2011 – December 25, 2019 (see text). The coefficient of correlation (R2) between the two signals was calculated on the basis of 2581 days (number of days for which a value is obtained using the OVPF method). An A^2 (Anderson-Darling normally test) value greater than 0.752 implies that the hypothesis of normality is rejected at 95% of significance. Populations are estimated with the maximum-likelihood test and 99% of significance (see Boudoire *et alii*, 2018). Based on the statistical analysis performed on signal of soil CO_2 degassing, resulting from the MAFILT algorithm, five distinct anomalies of soil degassing were identified in 2018.

COMPARISON OF THE CORRECTED SIGNALS						
METHODS	**N° STATIONS**	**N° DAYS**	**MEAN (a.u.)**	**1σ (a.u.)**	**A^2 (a.u.)**	**R^2 (a.u.)**
(1) OVPF	12	2581	0.45	0.16	13	0.7
(2) MAFILT	13	3281	0.42	0.17	92	
COMPARISON OF THE POPULATIONS						
POPULATIONS	**MIN (a.u.)**	**MAX (a.u.)**	**MEAN (a.u.)**	**1σ (a.u.)**	**Contribution (%)**	**Anomaly threshold**
(1) Population 1	0	0.32	0.25	0.06	21.5	0.61
(1) Mixed values	0.32	0.61	0.46	0.08	62.2	
(1) Population 2	0.61	1	0.70	0.08	16.3	
(2) Population 1	0	0.31	0.22	0.06	25.5	0.65
(2) Mixed values	0.31	0.65	0.44	0.08	57.5	
(2) Population 2	0.65	1	0.70	0.09	17.0	
LIST OF THE SOIL CO2 DEGASSING ANOMALIES						
DATE	**1st Anomaly**	**2nd Anomaly**	**3rd Anomaly**	**4th Anomaly**	**5th Anomaly**	
(2) Start	June 22th	August 20th	September 19th	October 13th	November 3rd	
(2) Maximum	June 27th	August 24th	September 23th	October 18th	November 5th	
(2) End	July 8th	August 27th	September 27th	October 28th	November 16th	

the LPT was subtracted from the HFF in order to obtain the Seasonal Component (SC) and finally iv) the SC was subtracted from the HFF. Therefore, in the final calculated series the seasonal component and all components with period shorter than one month were removed.

Another important aspect that deserves attention concerns the locations of the monitoring stations.

The locations had a strong impact on the measured data for different reasons, such as: the distance from the tectonic structure involved in degassing, the presence of aquifers which can partially dissolve CO_2 released from the degassing process and the local soil permeability. According to these factors, a volcanic event, such as a magma ascending towards the surface of the volcano, can produce very different soil degassing variations. In order to reduce the site effects, the signals were processed using the following equation proposed by Liuzzo *et alii* (2013), which produces a global normalized signal of soil CO_2 (hereafter referred to as ϕ^n_{Norm}), in which the stations have a comparable weight but no longer possess the flux physical unit of measurements.

$$\phi^n_{Norm}(t) = \sum_{i=1}^{n} \frac{\phi_i(t)-\phi_i^{\min}}{\phi_i^{\max}-\phi_i^{\min}}$$

where ϕ_i is the CO_2 flux at the i^{th} station, ϕ^{min} *and* ϕ^{max} are the minimum and maximum CO_2 flux, respectively and *t* is time.

The results of both data treatment protocols on the ETNAGAS CO_2 signal (Fig. 2) were verified in this study. Notwithstanding the fact that the protocols were based on very different algorithms, they produced similar results (R^2=0.7; Table 1). Thus, it can reasonably be confirmed that the filtered residual CO_2 signal accurately reflected the soil degassing, which was recorded by the ETNAGAS network without any possible environmental interference. It is noted that the MAFILT method allows to obtain a more complete time series (3281/3281 days) than the OVPF method (2581/3281 days). The latter requiring meteorological records with which to correct the signal. For example, if one station does may not record environmental parameters (i.e. temperaure and pressure) it will effect the entire protocol generating a data gap for the corresponding day. In contrast, the MAFILT method does not require the input of environmental parameters and thus is easier to use and more accurate. For this reason, CO_2 degassing using the MAFILT protocol will be discussed in the following.

Additionally, it was attempted to detect any period in the soil CO_2 degassing time series with an anomalous degassing rate. The maximum-likelihood test with a 99% level of confidence (see Boudoire *et alii,* 2018) was applied in order to identify two distinct populations within the time series (Table 1). A thorough analysis of the soil CO_2 signals from the ETNAGAS network revealed a statistical threshold of 0.65 of the normalized flux, indicating an anomalous degassing stage of the volcano; this was repeated five times in the second half of 2018. This excessive degassing rate was considered to be consistent with a new recharging phase of the pulsating plumbing system by new CO_2-rich magma, which occurred between June and November 2018.

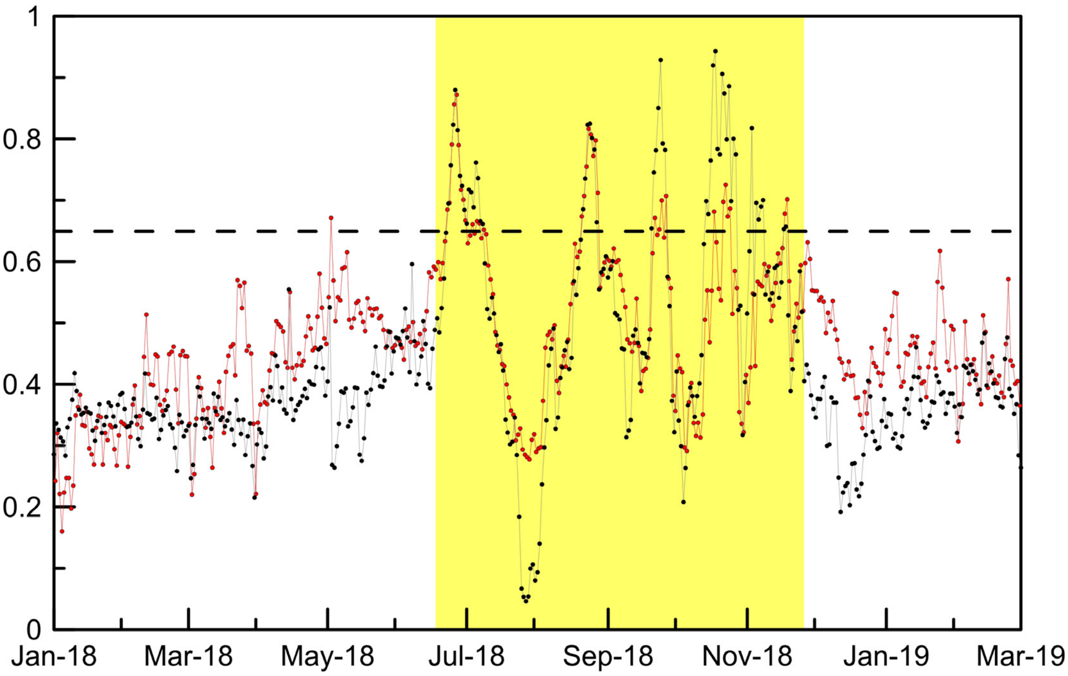

Fig. 2 - Normalized soil CO2 flux of the Mt. Etna geochemical network. In red, the signal provided by OVPS algorithm; in black, the same time-series after application of MAFILT. The yellow-shadowed area indicates the period when the Mt. Etna gas network recorded soil CO_2 flux exceeding a threshold, which was attributed to an anomalous degassing rate (see table 1). The OPVF and MAFILT algorithms are described in the text.

COMPARISON BETWEEN SOIL CO_2 DEGASSING, AND VOLCANIC AND SEISMIC ACTIVITY

It can be stated that 2018 was a period of important volcanic and seismic events on Mt. Etna. The day-signals recorded by six of the 14 stations by the ETNAGAS network are plotted in Figura 3 (MSM1, Maletto and Albano, located on the north-east side of the volcanic edifice; and SML1, SML2 and Parco Etna, located on the south-west side). Figura 3 underlines how the soil CO_2 signals recorded by monitoring stations were generally characterized by a very high level of synchronicity, albeit with appreciable variations in amplitude. Consequently, as previously described, the data were processed with the method proposed by Liuzzo *et alii* (2013).

Figura 4 shows the global CO_2 variation (calculated by the aforementioned equation) compared to volcanic and seismic activity occurring in 2018. On the left-hand part of this plot, the end of 2017 was marked by the final Strombolian activity of the former phase of volcanic activity, to be followed by a remarkably long 16-month period of quiescence. Both these elements support the assumption that the activity occurring during the second half of 2018 constitutes a new eruptive phase.

This new phase commenced in December 2017 with a weak but growing trend of the overall CO_2 flux during the quiescence period. The trend was thereafter interrupted by an abrupt increase in CO_2 fluxes, reaching a maximum towards the end of June 2018. The successive sharp decrease occurs prior to the beginning of a new and brief volcanic phase, consisting mainly of Strombolian activity at the BNC. Whilst it may be short-lived, this activity is a significant starting point of a renewed phase of volcanic activity, which is clearly correlated with increased gas pressure in the plumbing system. The similarity in the CO_2 signal drop after the 2018 BNC activity compared to the one recorded in 2013, when the activity at the same crater terminated (Cannata *et alii,* 2015), is also noteworthy. An anomalous CO_2 increment was later observed, with a maximum comparable to that previously recorded, and this increment was reached at the end of August 2018. A new, more intense and longer explosive phase occurred at the summit craters (NEC and NSEC) on the August 24, 2018.

Thereafter, before mid-September 2018, a new CO_2 episode commenced, reaching a maximum value a few days before the end of September 2018, which rapidly decrease at the beginning of October 2018 when an earthquake with a magnitude of M=4.6 occurred on October 6, 2018. The hypocentre of this event was located on the south-east side of Mt. Etna along the Ragalna faults, near the villages of Santa Maria di Licodia and Biancavilla, at a depth of approximately 9 km bsl. Within the 2018 chronology of activity on M. Etna, it is important to note that this earthquake was the first seismic event with a magnitude greater than 4 that occurred on Mt. Etna since the inception of the ETNAGAS network. The earthquake was relatively deep but sufficiently strong to be felt by the population living close to the epicenter.

The final and greatest soil CO_2 flux variations occurred after this seismic event and reached a relative maximum between in mid-October and early November 2018. Thereafter, a new volcanic phase commenced in mid-November 2018 with a decreasing trend, Strombolian activity and a lava flow at the NSEC crater. The volcanic activity during this phase was stable but not significantly vigorous and continued until December 24, 2018 when a new NNW- SSE oriented fracture opened on the flank of the SEC and rapidly propagated towards the south side of the Valle del Bove rim. Fortunately, the propagating fracture reduced the risk of a potential lava overflow along the southern flank of Mt. Etna, which represents the most populated region of the volcano. However, the lava emissions and Strombolian activity markedly persisted until December 26, 2018 producing an erupted volume of approximately 2.5 x 10^6 m^3 (INGV-OE reports,

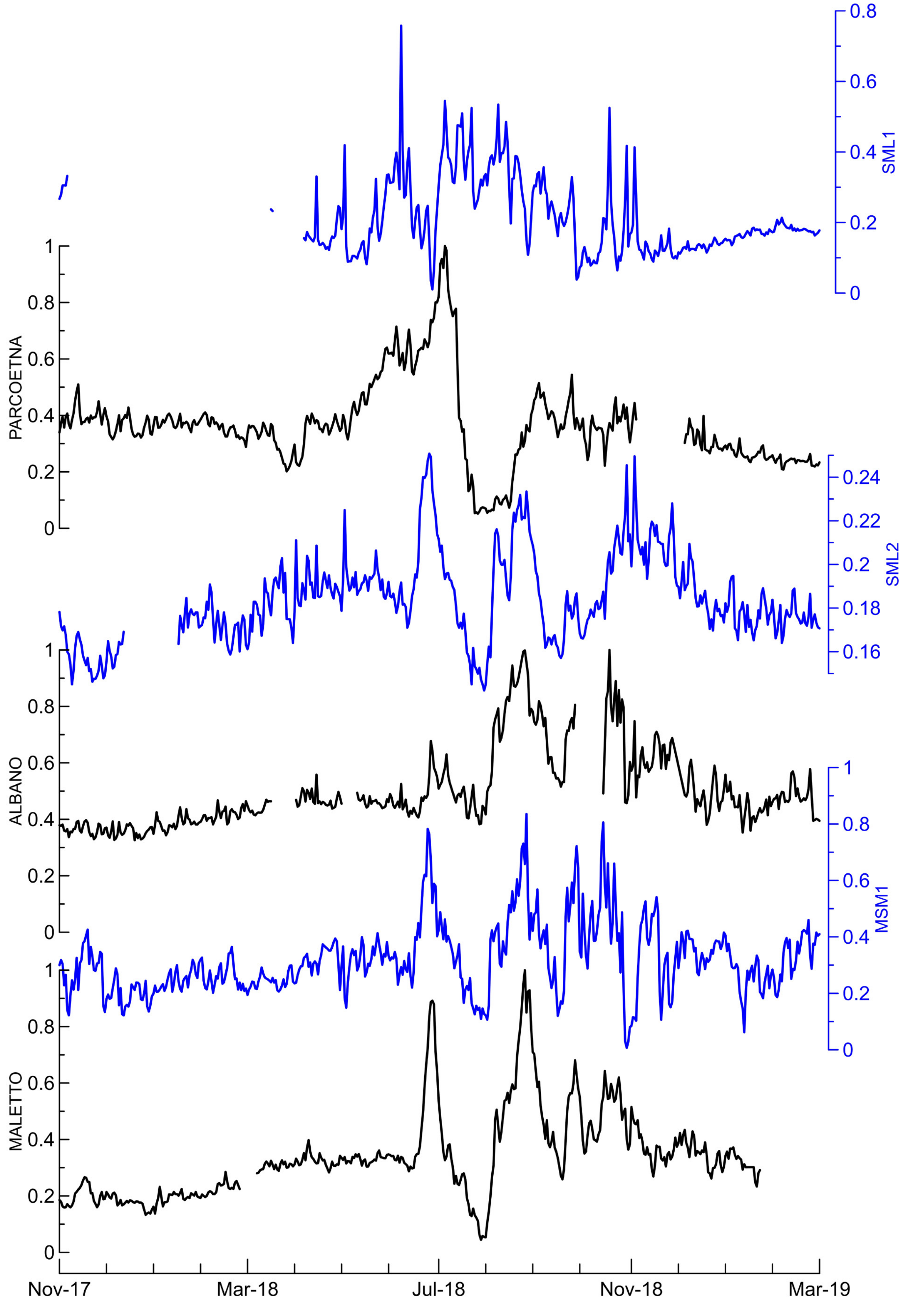

Fig. 3 - Normalized soil CO_2 flux of six monitoring stations sited on the western side of Mt. Etna volcano. The gas emissions highlight a significant synchronicity on this side of the volcano, although the amplitude values vary between different sites.

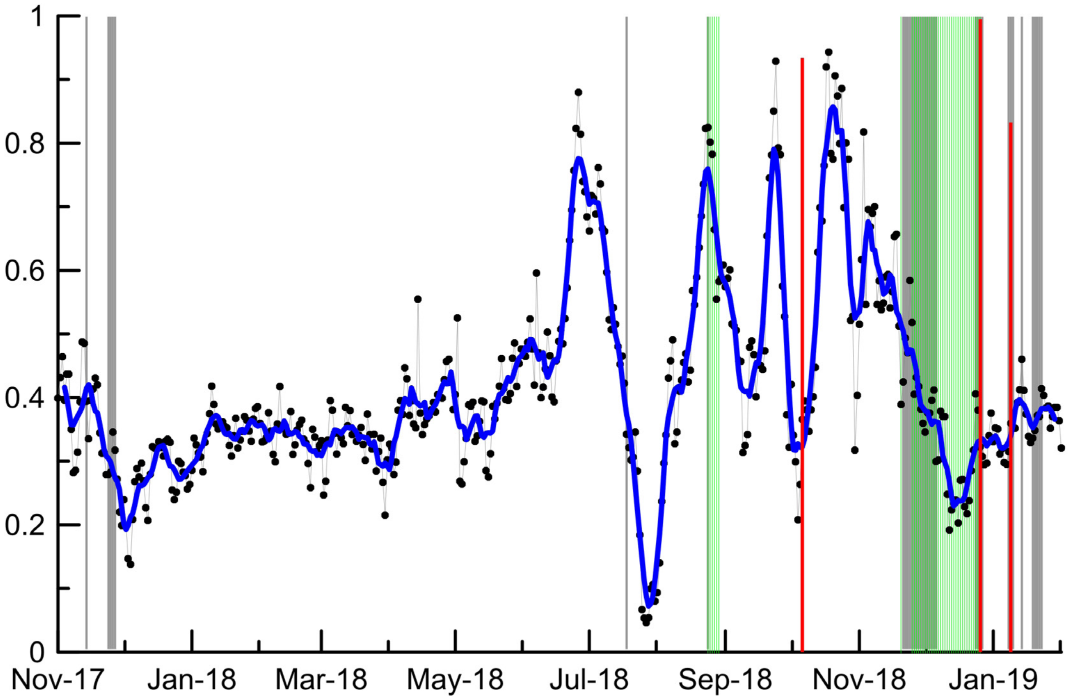

Fig. 4 - Normalized time series from the Mt. Etna gas soil CO_2 flux processed by the MAFILT algorithm, where the black points correspond to daily values. The blue line indicates the seven-day running average. The grey bars denote the occurrence of ash emission from the summit craters, the green bars indicate the Strombolian activity and lava emission episodes (no distinction between the different craters). The red bars indicate the occurance of the earthquakes. Noteworthy is the 16-months long interval of inactivity of Mt. Etna between December 2017 and July 2018, which is accompanied by an increase of the CO_2 flux, which ended with a remarkable acceleration in June 2018.

2017-2018). This event involved all the summit craters, which degassing rate suddenly increased, particularly the BNC which also produced a conspicuous volume of ash emission. In terms of intensity and duration, the activity in December 2018 can reasonably be considered the most important after the December 2015 eruption.

This final eruptive activity in late December was also characterised by the most intense earthquake in 2018, affecting the Fiandaca fault (south-east flank of Mt. Etna) and occurring on December 26, 2018 (2:19 a.m. UTC). The event of M=4.9 was located at less than 1 km depth (Civico *et alii,* 2019) and damaged the small villages of Fleri and Pennisi, the closest to the epicentre. The December 26, 2018 seismic event also coincided with the termination of the ongoing eruptive activity, occurring during a phase of minimum degassing rate.

After this event, the soil CO_2 signal recorded a new weak positive trend during January and February 2019, returning to the mean values of the CO_2 fluxes, as observed for this area during the quiescent period. Sporadic NSEC Strombolian activity was observed between January 8 and 23, 2019 , and an additional shallow seismic event (M=4.1) occurred on the eastern flank of the volcanic edifice, which represented the final volcanic activity in the 2018 eruptive cycle.

COMPARISON BETWEEN SOIL CO_2 DEGASSING AND CO_2/SO_2 RATIO IN-PLUME

The volcanic plume of Mt. Etna is monitored by a MultiGAS station located on the northern rim of the Voragine crater. INGV installed the first permanent MultiGAS station in 2006, and subsequently acquired an extensive dataset of plume measurements, which have provided invaluable information regarding the degassing process of Mt. Etna and for surveillance purposes (Aiuppa *et alii*, 2007, 2008, 2010). However, this method limited by the necessity the install the monitoring station in proximity to the volcanic vent to avoid scrubbing effects in particular those of SO_2. In addition, another significant limitation is related to a possible undesirable wind direction, which may direct the plume gases away from the recording station. These limitations forced the installation of the MultiGAS station as close as possible to the emitting vent, at sites which are exposed to the toxic and acidic gases of the plume and potential ballistic, Strombolian activity. Thus, recording the CO_2/SO_2 ratio cannot always be continuous and only sporadic measurements of this ratio were possible on Mt. Etna in 2018. Nevertheless, a relatively good correlation between soil CO_2 degassing and the CO_2/SO_2 ratio variations for 2018 can be seen in Figura 5. As modelled by Aiuppa *et* al 2006, 2012, the CO_2/SO_2 ratio exhibits cycles of increases and decreases, which occurred before the volcanic activity. As was the case with variations in soil CO_2 flux, this may indicate a progressive movement of new batches of magma towards the shallow plumbing system. Liuzzo *et alii* (2013) already demonstrated a correlation between the CO_2/SO_2 variations and those of soil CO_2 with an interpretative model regarding Mt. Etna. As predicted by the model of Liuzzo *et alii* (2013), when the input of new batches of CO_2-rich magma ascends from the deeper part of the Mt. Etna magmatic system, variations in soil CO_2 flux and the CO_2/SO_2 ratio correlate well. The lack in correlation between the two signals is observed during periods of passive degassing in the absence of magma progression towards the surface or when a shallow part of the plumbing system is still active. In this case, the CO_2/SO_2 ratio trend can be relatively higher when compared with the soil CO_2 peripheral flux trends. This latter condition was to be observed after the eruption terminated during the first months of 2019.

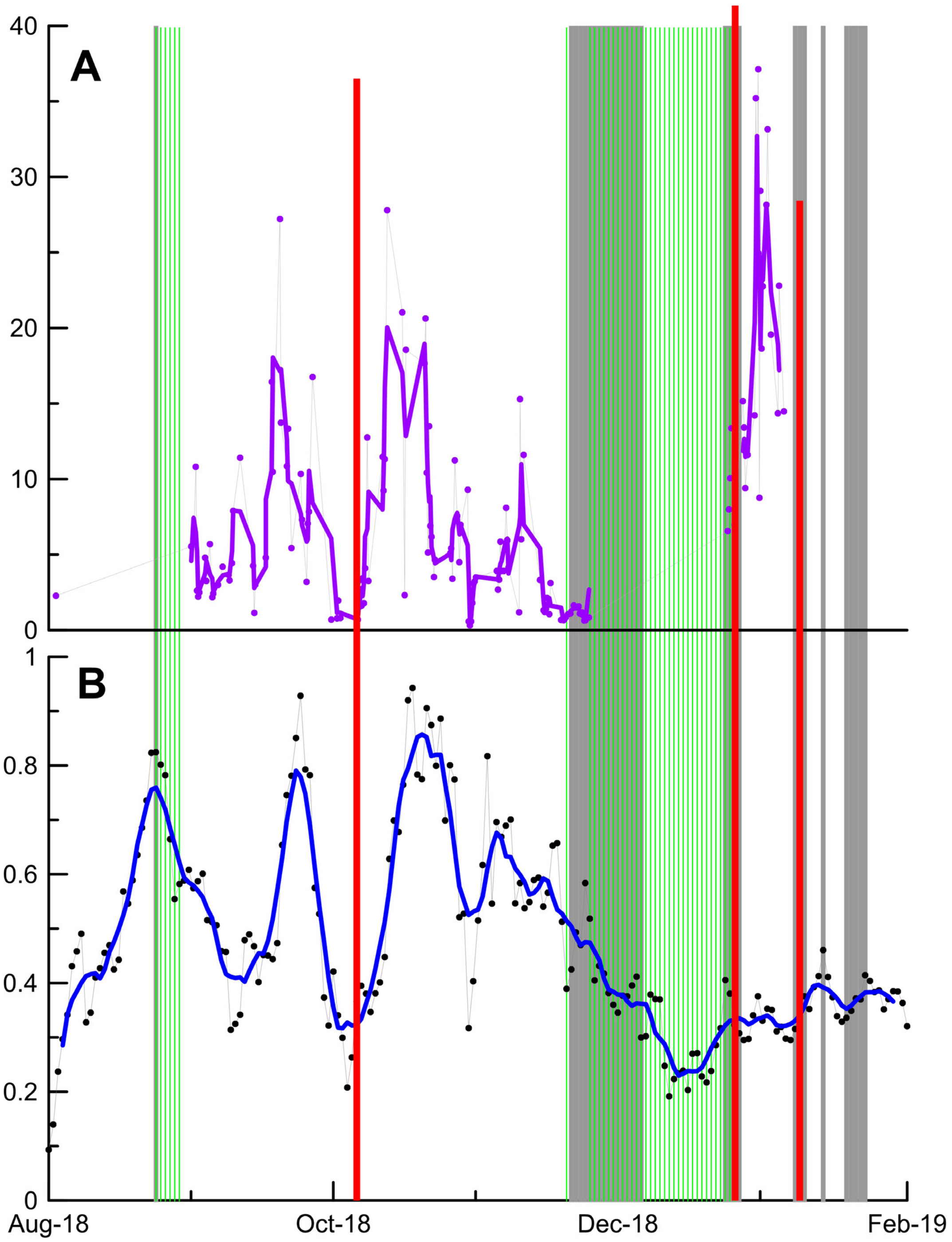

Fig. 5 - Comparison of the geochemical signals recorded by the INGV networks. A) CO_2/SO_2 ratio from the VOR station sited on the north rim of Voragine crater (see also figure 1); the purple points correspond to the raw data, while the purple line is the running average based on three consecutive points. B) Soil CO_2 flux of gas network (bars as in figure 4). The CO_2/SO_2 ratio shows discontinuities due to technical problems as well as periods of non-favourable wind directions. However, when it was possible to acquire plume gas and soil CO_2 gas simultaneously, the signals reveal periods of good correlation followed by a period without correlation, corresponding to different "volcanic condition" as explained in the text and in figure 6.

CONCEPTUAL MODEL OF THE MT. ETNA DEGASSING ACTIVITY

The patterns of increased and decreases in degassing preceding eruptions on Mt. Etna are well documented (Gurrieri *et alii*, 2008, Liuzzo *et alii*, 2013). The variations in geochemical signals (soil CO_2 degassing and CO_2/SO_2 plume ratio) observed on Mt. Etna between 2018 and January 2019, and the relationships with volcanic activity are the focus of this paper. Of particular interest is the occurrence of three seismic events of a magnitude M >4 during the intense period of volcanic activity.

The time-series shown in Figs. 4 and 5 reflect: i) the geometry of the networks (number and locations on the monitoring stations) (Liuzzo *et alii*, 2013); ii) the physics of CO_2 and SO_2 dissolution in the magma (Gerlach & Terrence 1986; Blanck *et alii*, 1993; Carroll & Holloway 1994; Hollowey *et alii*, 1994); and iii) the consistency with the typical CO_2 content in fluid inclusions from the Etnean basalts (Kamenetsky & Clocchiatti, 1996; Spilliaert *et alii*, 2006). The over-saturation of CO_2 in Etnean magma begins at a depth of approximately 20 km but the greatest volume of CO_2 is released from magma at a pressures of approximately 200-300 MPa, corresponding to a depth of 8-10 km (Aiuppa *et alii*, 2007). However, SO_2 being much more soluble than CO_2, the exolution of this gas occurs at lower pressures, and is considered as a marker of a shallower degassing condition that can be expected at depths of 2-4 km. According to the gas solubility models (e.g., Dixon, 1997; Papale, 1999; Moretti *et alii*, 2003; Moretti & Papale, 2004; Lesne *et alii*, 2011), the data presented in this paper indicate that the strongest variations in signal amplitude, which in turn suggest a pressurisation phase in the plumbing system, always occur prior to the commencement of explosive and eruptive volcanic activity, lasting for a period of a few to 10 days. Therefore, the eruptive and explosive activity observed during 2018 and the first month of 2019 is likely resulting from the intermittent arrival of new batches of volatile-rich magma from the Etnean volcanic system. This results in anomalies in the gas flux and in the CO_2/SO_2 ratio during the progressive migration towards the surface, as recognized for previous eruptive episodes by several authors (e.g., Aiuppa et alii, 2007; 2010; Patanè et alii, 2013; Cannata et alii, 2015)

As an initial attempt to clarify the interpretative model proposed in this study, the volcanic processes in relation to the overall plumbing system can be divided into two main stages:

1) the early magma inputs fed the deeper Etnean plumbing system, thereby causing the Strombolian activity at BNC, the temporary reactivation of the NESC (September 2018) and, finally, the seismic event in October 2018. The latter revealed a large magnitude (M=4.6) which occurred at a relatively great depth (approximately 8.5 km). This event was probably caused by the initial phase of magma intrusion, inducing stress in the deeper zone of the Etnean edifice. This phase markedly involved the deeper plumbing system.
2) The subsequent phase of magmatic input (October-November 2018) was characterised by an increased volume of magma, which filled the upper part of the plumbing system. Depressurization and consequent progressive transfer towards the surface of the volcano caused the subsequent eruptive phase in December 2018. The latter was characterised by the most violent activity, with the opening of the fracture on the December 24, 2018, and a destructive, shallow earthquake on December 26, 2018 (M=4.8; at approximately 1 km depth), which produced substantial damage to the village of Fleri. It is noted, that the eruption quickly ended after this seismic event and only one additional seismic event (January 9, 2019 M=4.1; at approximately 1 km depth) was registered in the area. It is noteworthy that during the period between these two earthquakes, a lack in correlation between soil CO_2 flux and the CO_2/SO_2 ratio was observed. This phase mainly involved the upper part of the plumbing system, and it was characterized by enhanced gas drainage condition from the main volcanic conduits (chimney effect). Therefore, this constitutes an almost complete degassing in the main summit craters with no involvement of the peripheral flank of Mt. Etna.

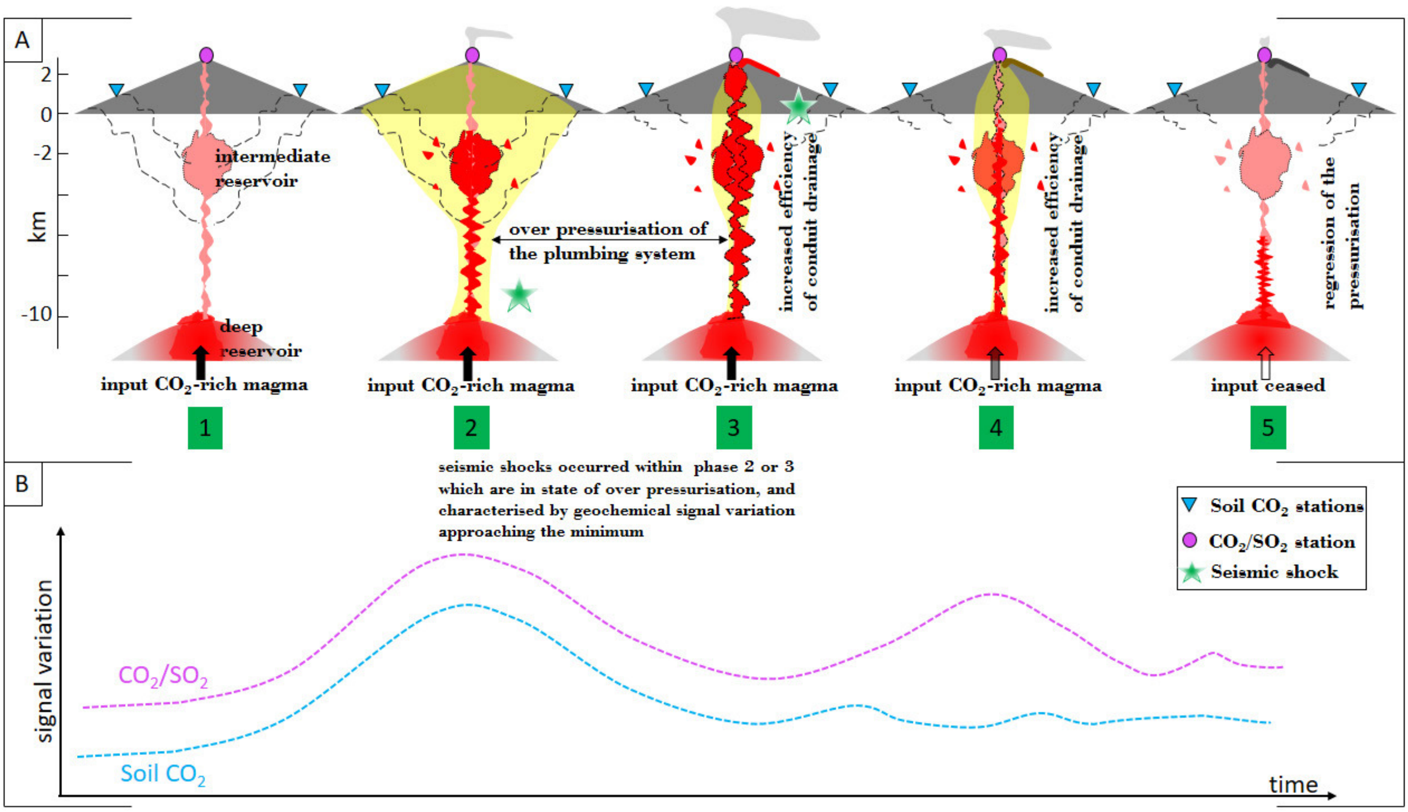

Fig. 6 - Schematic interpretative model of different stages of "volcano conditions" where the main steps of volcanic activities are summarised. A) Five different conditions are indicated (see text). In this scheme the transition between two consecutive steps is considered reversible, i.e., they may occur intermittently, as suggested for stages 1 and 2 from June to November 2018 (see text). B) The theoretical variation of both soil CO_2 flux and CO_2/SO_2 ratio is reported in relation to the volcanic condition described in the scheme (A).

A conceptual model for the recent eruptions of Mt. Etna is proposed in Figura 6, which shows five different “volcanic stages”, corresponding to specific “degassing condition effects”.

Step 1 - The Mt. Etna plumbing system is characterized by an input of magma, which fills the deeper reservoir. This initial condition started with weak geochemical signals, since it is preceded by an extensive period of quiescence.

Step 2 - The gradual evolution from the step 1 to 2 is accompanied by the supply of volatile-rich magma into the plumbing system. The refilling and the depressurization of the magma facilitated the movement in the intermediate reservoir zone. The migration of magma to a lower pressure determines the first, important degassing process with an excess of CO_2 outgassing; the latter recorded as an increase in soil CO_2 flux, in addition to a greater CO_2/SO_2 ratio. Intermittent magmatic input determined a repetition of transition between steps 1 and 2, as recorded between June and September 2018. The reversal from the step 2 to 1 would constitute a temporary exhaustive effect of the initial magmatic input, thereby causing a decrease in soil CO_2 flux and CO_2/SO_2 ratio. The transition and reversal between steps 1 and 2 and the induced CO_2 degassing variations can be considered as cycles of the volcanic activity. An important consequence of this volcanic condition is concerned with the induced stress in the deeper part of the plumbing system. It is reasonable to assume that this increas in stress triggered the October 6, 2018 earthquake.

Step 3 - As the magma continues to feed the plumbing system it may have sufficient mass/volume to feed the entire volcanic conduit, propagating into the upper part of the system. This condition facilitates the outgassing of SO_2 from the magma, which already lost part of its less soluble CO_2 contents. Calvari et al. (2020) demonstrated a constant increase in the SO_2 flux from Mt. Etna, reaching a peak value on December 26, 2018 (Figura 10 in Calvari et al. 2020). However, as indicated in the weekly Etna monitoring report (INGV-OE reports, 2017-2018), after the SO_2 decreasing flux of 26 and 29 December 2018, a new peak in SO_2 flux was recorded, with a maximum value occurring in the first half of January 2019. It can be considered reasonable to expect three significant effects regarding the pre- and syn-eruptive phases : i) the main volcanic conduit will start acting like a chimney, thereby facilitating the drainage of the gas from the summit craters. As a consequence, less gas is discharged from the peripheral area, and the soil CO_2 flux and CO_2/SO_2 ratio is expected to decrease (Figura 5 refers to the period between the second half of October 2018 and the second half of November 2018); ii) the magma, which was pushed into the shallow portion of the Etnean edifice, has increased the mechanical stress in the shallow sub-surface of the volcano. The increased mechanical stress triggered seismic events at shallow depth; iii) close to the surface, the arrival of magma easily evolved into eruption activities. The December 2018 eruption and the two following seismic events can be attributed to this step.

Step 4 - At the end of the eruption (lava flow, Strombolian activity and lava fountaining ceased on the December 27, 2018 - Calvari et al. 2020), the dynamics of the volcanic conduits can be characterised by a chimney effect, demostrated by the high plume degassing rate and low soil CO_2 flux in the peripheral areas. As previously mentioned, the SO_2 flux recorded at the end of the eruption (after December 27, 2018) and until the first half of January 2019 (INGV-OE reports, 2017-2018) reached a maximum value concurrently to the CO_2/SO_2 ratio. This implies that the plume CO_2 flux (estimated by coupling of the CO_2/SO_2 and SO_2 flux) should also have been at its maximum rate for the period under observation. The decreasing soil CO_2 flux recorded concurrently in the peripheral areas can be attributed to three factors: i) improved drainage efficiency regarding the gas of the main volcanic conduits; ii) filling of the entire conduit system by magma (even if the lava output stopped), thereby inducing the degassing of renewed input of CO_2 at depth and SO_2 from the shallower plumbing system (probably facilitated by further post-lava output depressurization); and iii) the main pathway for degassing is now determined by the chimney effect, significantly reducing the gas discharge on the volcano’s flank.

Step 5 - At the final stage of the eruption, a regression in pressurisation involved the entire plumbing system. The ceased input of magma reduced the level of all activity, thereby transitioning towards a period of quiescence, which can be compared to the first phase of (Step 1), concluding the process. Soil CO_2 flux and the CO_2/SO_2 ratio should transition to lower values, in line with correlation trends.

CONCLUDING REMARKS

This study analysed the time-variation of the volcanic gas emissions and soil gases on Mt. Etna, using data from the INGV geochemical network, to construct an interpretative model of the 2018 eruption stages of Mt. Etna volcano. The pre-syn-post eruptive observations outlined in this study allowed to conclude that the early phase of pressurisation of the Mt. Etna plumbing system began on June 2018 and intermittently continued until November 2018. The effects of this pressurization induced volcanic activities, varying from ash emissions to the violent eruptive episode of late December 2018. Moreover, for the first time since the inception of the INGV geochemical networks, three earthquakes with M>4 were recorded. The time-variation of volcanic gas emissions recorded at Mt. Etna underlined various aspects that could be applied to other volcanic systems worldwide:

1) the geochemical networks on Mt. Etna registered marked variations in soil CO_2 flux and the CO_2/SO_2 ratio in the volcanic plume; this assisted in identifying distinctive phases of pressurization in the plumbing system;
2) all earthquakes (M>4) occurred during phases of minimum gas rate variations, which in turn followed stages of pressurization affecting different portions of the plumbing system;
3) the coherency in the soil CO_2 flux and the CO_2/SO_2 ratio behaviour offered further proof to the efficacy of gas geochemistry as a pivotal monitoring tool in understanding volcanic activity. Furthermore, it demonstrates the invaluable role of the soil CO_2 network for surveillance purposes due to its robustness and reliability.

The authors of this paper contend that the observations described herein provide stimulating avenues of research in exploring the possible interconnected dynamics between degassing patterns and seismic activity in volcanic environments. Thus, the crucial role played by volcanic volatile emissions in analyzing volcanic activity can once again be confirmed.

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