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Changes in CO_2 Soil Degassing Style as a Possible Precursor to Volcanic Activity: The 2019 Case of Stromboli Paroxysmal Eruptions

Salvatore Inguaggiato [1,*], Fabio Vita [1], Marianna Cangemi [2] and Lorenzo Calderone [1]

[1] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Palermo, Via Ugo La Malfa, 153-90146 Palermo, Italy; fabio.vita@ingv.it (F.V.); lorenzo.calderone@ingv.it (L.C.)
[2] Dipartimento di Scienze della Terra e del Mare, Via Archirafi 36, 90123 Palermo, Italy; mariannacangemi@gmail.com
* Correspondence: salvatore.inguaggiato@ingv.it; Tel.: +39-091-6809435

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Abstract: Paroxysmal explosions are some of the most spectacular evidence of volcanism on Earth and are triggered by the rapid ascent of volatile-rich magma. These explosions often occur in persistently erupting basaltic volcanoes located in subduction zones and represent a major hazard due to the sudden occurrence and wide impact on the neighboring populations. However, the recognition of signals that forecast these blasts remains challenging even in the best-monitored volcanoes. Here, we present the results of the regular monitoring of soil CO_2 flux from a fumarole field at the summit of Stromboli (Italy), highlighting that the 2016–2019 period was characterized by two important phases of strong increases of volatile output rate degassing (24 g m^2 d^{-2} and 32 g m^2 d^{-2}, respectively) and moreover by significant changes in the degassing style few months before the last paroxysmal explosions occurred in the summer 2019 (3 July and 28 August). Establish that the deep portions of a volcano plumbing system are refilled by new volatiles-rich magma intruding from the mantle is therefore a key factor for forecasting eruptions and helping in recognizing possible precursors of paroxysmal explosions and could be highlighted by the monitoring of soil CO_2 flux. The abrupt increase of degassing rate coupled with the strong increase of fluctuating signal (daily natural deviation) recorded during 2019 at Stromboli could be the key to predicting the occurrence of paroxysmal events.

Keywords: Stromboli volcano; geochemical monitoring; CO_2 degassing; paroxysmal activity

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1. Introduction

Stromboli (Figure 1) is the northernmost of the Aeolian Islands, a volcanic archipelago located off the northern coast of Sicily (Southern Italy). Here, a persistent volcanic activity takes place from several vents located within a crater terrace at 750 m a.s.l. in the upper portion of the Sciara del Fuoco. Its eruptive style is characterized by 5–20 Strombolian explosions per hour [1] with a large amount of actively and passively gas emitted through several small eruptive vents located in the crater terrace, within which we can recognize three main features—namely, the northeast (NE), the central (C), and the southwestern (SW) vents. In addition to the summit degassing, a peripheral discharge of gas, due to dissolved volatiles from the coastal aquifer and soil degassing controlled by tectonic discontinuities, has to be considered.

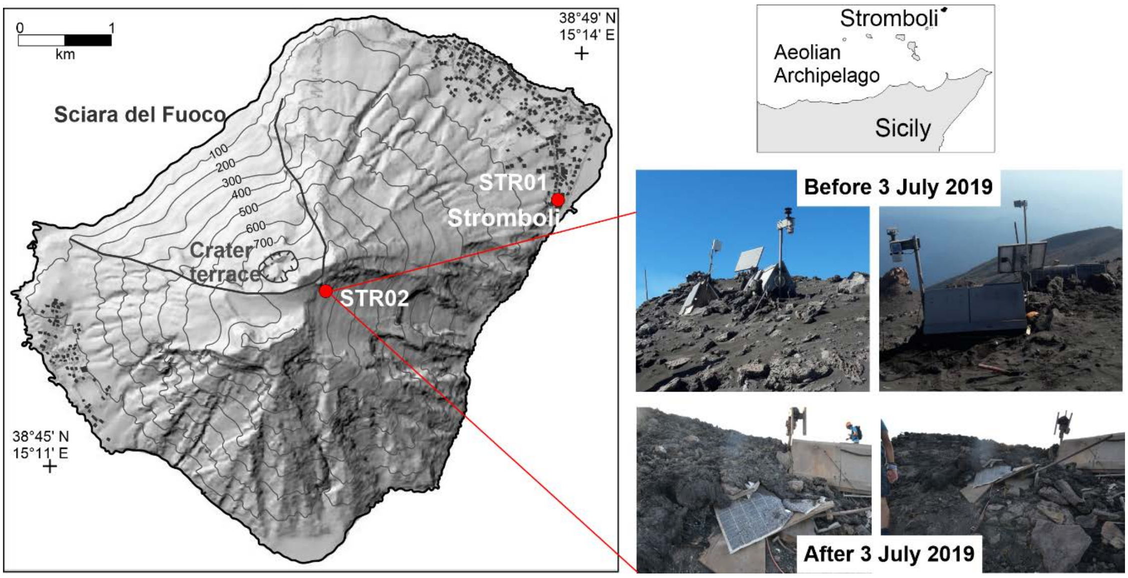

Figure 1. Stromboli map with the location of the STR02 and STR01 stations (CO_2 fluxes measurements) on the summit and peripheral areas of the volcano in the Pizzo sopra La Fossa and Scari, respectively. Pictures of the STR02 equipment before and after the 3 July 2019 paroxismal events have been inserted.

Strombolian activity is sustained by a delicate dynamic equilibrium between deep input and shallow volatiles magma degassing [2]. Fluids are continuously released by magma convection in a shallow magma reservoir, during which the ascending less-dense gas rich-magma substitutes the denser degassed magma that in turn sinks down [3–5]. The shallow magma reservoir releases volatiles composed of H_2O, CO_2, SO_2, H_2S, HF, and HCl (condensable gases), and some non-condensable gases (e.g., He, H_2, N_2, CO, CH_4) during both eruptive activity and inter-eruptive periods [6–8]. Variations between passive degassing and Strombolian activity is recorded in the gas geochemistry, which suggest a shallower magma body within the upper conduits that feed the former degassing and CO_2-rich gas bubbles coming from major depths (>4 km) [5].

The persistent activity of the volcano, characterized by passive degassing and mild Strombolian activity, is sometime interrupted by effusive eruptions, major and paroxysmal explosive events.

In the last three decades, four effusive eruptions occurred in 1985, 2002–2003, 2007, and 2014, two of which characterized by paroxysmal events (5 April 2003 and 15 March 2007). The 2002–2003 eruption took place after a long period of absence of effusive activity after the previous one in 1985, allowing the superficial system to recharge in gases and to increase its eruptive/explosive potential. This effusive eruption, which began on 28 December 2002 and ended on 22 July 2003, was the longest in the last period, lasting 206 days and leaving the surface system of the island of Stromboli poor in gas. Instead, the next eruptions that occurred in 2007 and 2014 were much shorter (only 35 and 105 days, respectively) and were characterized more by a structural weakness of the volcanic building than by a real uprise of deep magma in large quantities. In fact, the amount of lava emitted during these last two eruptions was correlated with the emptying of the magmatic column from the top to the bottom and regulated by the height of the fracture that triggered the effusive eruption [9]. After the 2014 effusive eruption, a low eruptive activity period was recorded until May 2017, when more intense explosions started [10,11]. Since then, nine major explosions and two overflows occurred between July 2017 and December 2018 [10]. In particular, four major explosions occurred in 2017 (26 July, 23 October, 1 November, and 1 December), and five occurred in 2018 (7 and 18 March, 24 and 26 April, 18 August). The two overflows were recorded on15 December 2017 and 6 December 2018, respectively. The 2017 major explosions occurred from the central and/or south-western crater vents, whereas in 2018 explosive activity was more distributed among the three main craters [10]. Both overflows occurred from the north-eastern crater vent [10].

These intense activities were recorded by a multiparametric monitoring system, composed of seismic, geodetic, video-camera, and geochemical networks [10,11].

Usually, the activity state of a volcano can be monitored by geochemistry approach, using data from (i) fumaroles, (ii) diffuse soil degassing, (iii) geothermal waters, and (iv) crater plumes, acquiring both intensive (chemical and isotopic composition of fluids) and extensive (volatiles output) parameters for formulating and/or validating the fluid degassing model able to identify changes in volcanic activity.

The monitoring of extensive parameters like continuous soil CO_2 flux at volcanoes represents an important tool in hazards prediction, which has huge potential relevance for society that, coupled with the intensive parameters like CO_2 amount and isotopic composition of helium dissolved in the basal thermal aquifer, can give a complete picture of the state of volcanic activity [2,9,12–19].

2. Recent Volcanological Activity: The 2019 Paroxysmal Events (3 July and 28 August)

On 3 July 2019 at 14:46 UTC (16:46 local time), the monitoring system of INGV recorded a paroxysmal event in the south-central section of the crater terrace. Two minutes before the onset of the event, overflows had spilled out all the active vents. The paroxysm was preceded by two lateral blasts from the same vent and few seconds later a giant lava bubble burst out, followed by an eruptive column of gas and incandescent materials (bombs, lapilli, and ash) more than 3 km high over the summit area.

The column dispersed in a south-western direction, and a pyroclastic flow ran to the sea along the Sciara del Fuoco, generating a small tsunami (about 30 cm high). The fallout of the erupted materials covered the entire summit area, destroying the monitoring networks there installed. Moreover, a significant portion of the crater terrace (the north-east cinder cone) collapsed and was englobed in the pyroclastic flow. Fortunately, the explosion of 3 July occurred at 15:50, when there were no people in the summit area, thus avoiding casualties.

Unfortunately, an unusual lateral collapse of hot pyroclastic material arrived in the Punta dei Corvi area (close to Ginostra Village) in the south-west side of the island, killing a person walking at around 150/200 masl, well below of the 400 m of altitude indicated as the safety limit for people. Volcanic products from the column fell mainly in the village of Ginostra, causing widespread vegetation fires.

The inter-time between the two paroxysms was characterized by intense volcanic activity, including very frequent strombolian explosions, intense spattering, lava overflows (sometimes reaching the sea), and major explosions.

The second paroxysmal sequence, composed of three events with an overall duration of 20 s, occurred on 28 August 2019, 10:17 UTC (12:17 local time). It produced a 4-km-high eruptive column and a pyroclastic flow along the Sciara del Fuoco, which reached the sea and travelled over the sea surface for several hundreds of meters. This sequence was preceded the day before by an increment in Strombolian activity accompanied by the cessation of the lava flow, which resumed after the paroxysms reaching the sea few hours later.

As occurred in the previous 2003 and 2007 events, these paroxysms were propelled by the fast rising of low porphyric (LP) gas-richmagma from the deeper portion of the plumbing system [10,20–22].

3. Methods: CO_2 Fluxes Geochemical Networks

The volcanic activity of Stromboli volcano has been largely monitored in the last 20 years utilizing the continuous and discontinuous fluids geochemistry networks that have been installed and utilized by the INGV Palermo in the framework of the agreement between INGV and Italian Civil Protection for the monitoring program of Italian active volcanoes.

In particular, a geochemical network of soil CO_2 degassing using an automated accumulation chamber system (manufactured by West Systems, Pontedera, Pisa, Italy) [23] was installed in 1999 [2,24–26] in the summit and peripheral areas of Stromboli (Figure 1), which are characterized by anomalous soil degassing [27] located in Pizzo Sopra la Fossa and Scari [9,15].

The continuous monitoring of CO_2 fluxes is performed on an hourly basis (near real-time measurements), and the data are transmitted to the COA Civil Protection Volcano Observatory at Stromboli via Wi-Fi, from which it is sent to the INGV-Palermo geochemical monitoring center via a virtual private network [15].

The continuously acquired data of the CO_2 fluxes monitored by this geochemical network had a return of 87% of useful days acquired in the twenty years of monitoring [9,11,15]. The high-frequency acquisition of these data and the high performance of our geochemical network well supported the strombolian geochemical monitoring for the evaluation of its volcanic activity level in the last two decades.

4. Discussion

The explosive activity of a volcano is driven by the fluids dissolved in the magma which determine its energy and characterize its degree of explosiveness. CO_2 is the predominant component of the dry composition of volcanic fluids and is normally monitored to assess the level of volcanic activity [2,5,11,24,25,28–31]. Furthermore, considering its lower solubility coefficient in magmas compared to other volcanic gases such as SO_2, CO_2 begins to be released at greater depths and can follow the degassing of magmas from the depth to the surface.

For this reason, the monitoring of an extensive parameter such as the CO_2 soil flux represents one of the most useful tools to evaluate the volcanic activity level. Coupling this information with other geochemical intensive parameters, like fluid isotopes, ratios of chemicals in the plume, and geophysical parameters, can help to improve the comprehensive model of the plumbing system and make forecasting more constrained.

In the case of the Stromboli volcano, the monitoring of soil CO_2 degassing began in 1999, and presently, we have a dataset unique in the world, with over 20 years of data on an hourly basis. This impressive database [2,9,11] allowed us to verify the CO_2 degassing models with the effusive activities and with paroxysmal activities that took place in the last two decades.

Near-real-time measurements of soil CO_2 flux carried out in a fumarole field (STR02 station) located at the summit of Stromboli showed strong fluctuations likely described by an average increasing trend in the period 2005–2018 [9,11], interrupted by several abrupt changes of CO_2, which is a signature of the input of magmatic volatiles [9,11].

This average increasing trend determine a long lasting modification, with a positive increasing of 4.1 g m^2 d^{-2} [11] of CO_2 flux, which was explained by the slow but continuous increase of the total volatile pressure in the shallow plumbing system of Stromboli [9,11] due to a continuous refill from the depth. The flux of gases released from the new magma was higher than that from superficial degassing. The average degassing rate was determined from the difference between the daily degassing rates at the beginning and at the end of the period divided by the number of days in that period [11].

In the period 2016–2018, a new abrupt and strongly increasing rate of CO_2 degassing (24 g m^2 d^{-2}) was also recorded, indicating the degassing of volatiles related to a new magmatic recharge that caused transient modifications of the summit volatiles fluxes reaching the value of 23,000 g m^2 d^{-1} (Figure 2A). After a period of no data acquisition for technical problem (May–September 2018), the CO_2 flux suddenly incremented from October 2018 (3000 g m^2 d^{-1}) to April 2019 overcoming the value of 10,000 g m^2 d^{-1}, with an average rate of 32 g m^2 d^{-2} (Figure 2B).

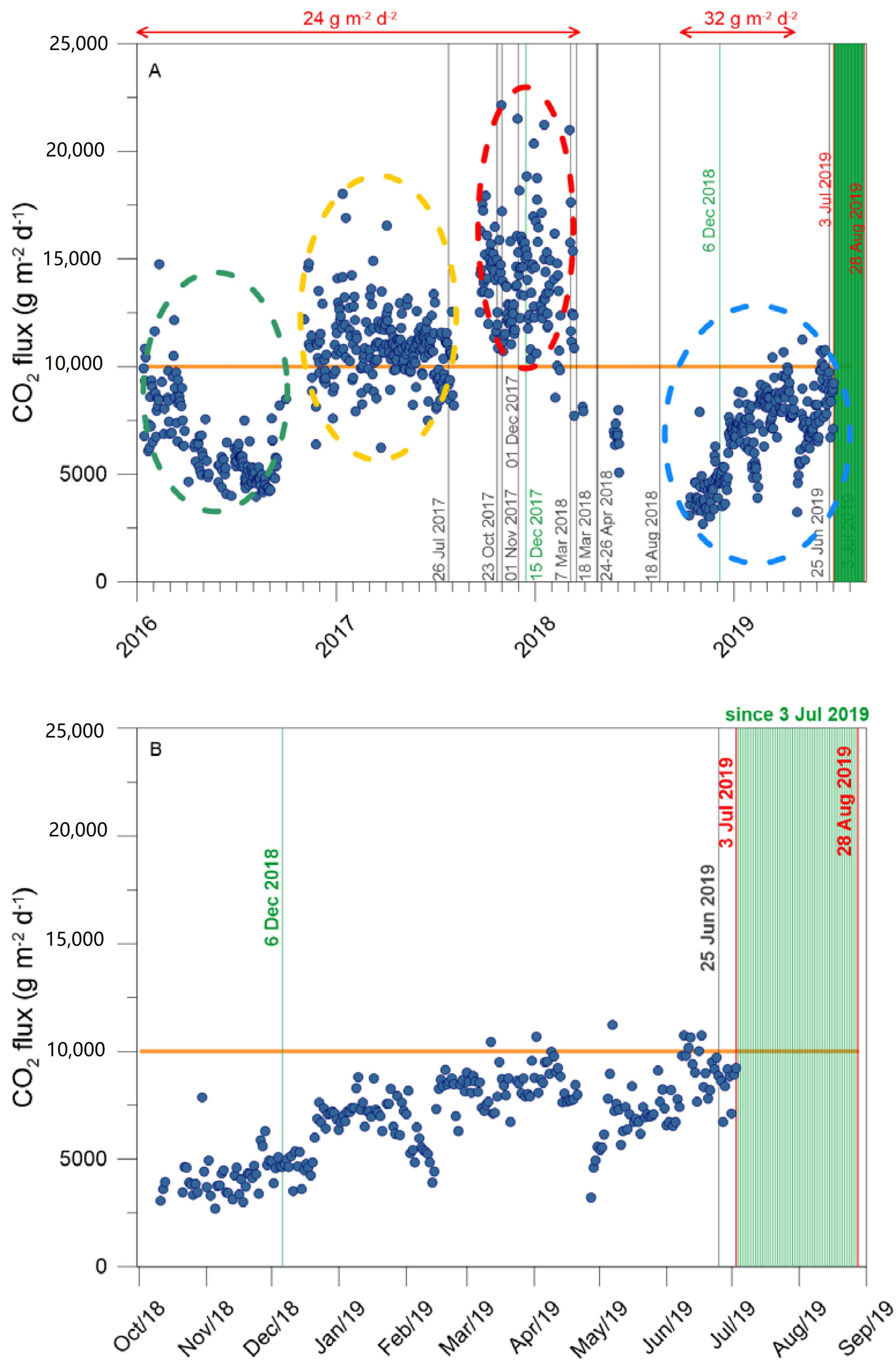

Figure 2. (**A**) Daily average of CO_2 fluxes at STR02 station expressed in g m^2 d^{-1} of the 2016–2019 period. Two abrupt increasing of CO_2 flux has been recorded. The green-yellow and red dashed circle indicating the first abrupt increasing of CO_2 fluxes (24 g m^2 d^{-2}) occurred in the 2016–2018 period; The dashed blue circle indicates the second abrupt increasing of CO_2 fluxes (32 g m^2 d^{-2}) occurred from October 2018 to July 2019.The threshold value of 10,000 g m^2 d^{-1} of CO_2 fluxes (orange line) have been reported; (**B**) Inset of daily average of CO_2 fluxes from October 2018 to July 2019; the threshold value of 10,000 g m^2 d^{-1} of CO_2 fluxes (orange line) have been reported. Colored vertical lines represent main paroxysms (red), major explosions (grey), and overflows (green).

Finally, a new degassing phase (Figure 3A,B) started in April–May 2019, characterized by a high natural daily variation (NDV), expressed as normalized standard deviation in % [2] culminated at the end of June with values >40%.

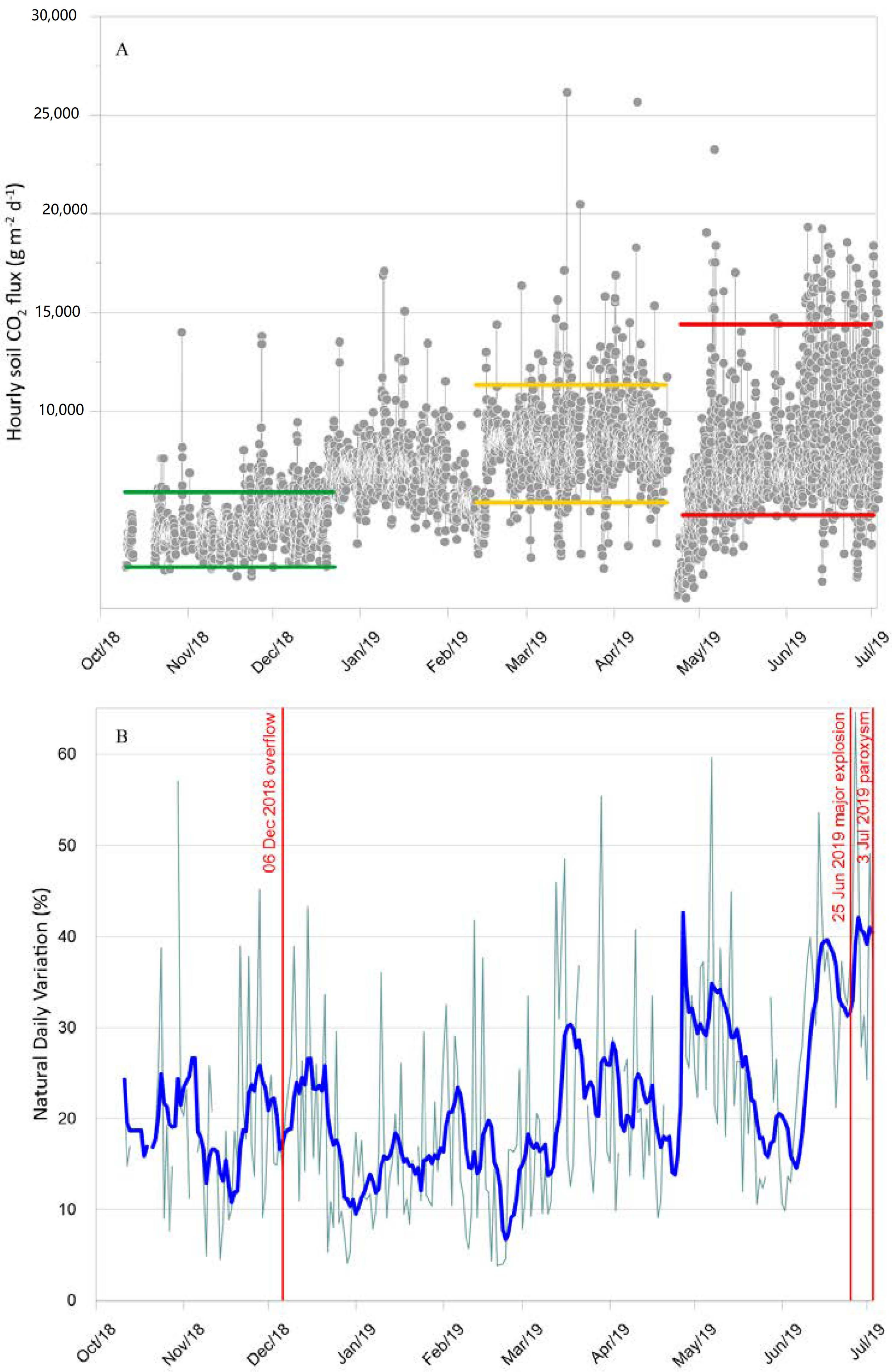

Figure 3. (**A**) Hourly CO_2 fluxes of STR02 in the period from October 2018 to July 2019. Changes in the style of shallow degassing (green horizontal line represents the background level) with a progressively increased variability of daily CO_2 fluxes have been observed in March and May, as evidenced by yellow and red lines. (**B**) Natural daily variations (NDV; [2]) of hourly CO_2 fluxes expressed as daily (24 measurements) normalized standard deviation in per cent [2]. The blue line is the weekly average value of NDV, which showed a significant increment from March 2019 up to early July.

This new strong increase of NDV% marked the begin of a new degassing style, characterized by a great disequilibrium between input/output degassing in the shallow volcanic system due to the strong increased volatile pressure.

In this very anomalous framework of outgassing from soils in the summit areas, on 3 July 2019, a sharp and deep input of magma and gas arrived at the summit craters, producing a high-energy paroxysm with a column of gas and ash with a height of about 5 km (Figure 4).

Figure 4. Pictures of the 3 July paroxysm at Stromboli volcano (photo courtesy of Gabriele Scognamiglio).

Understanding the shallow processes by studying data patterns and trends is useful for assessing the actual risks due to potential explosive unrests. In particular, these kinds of studies have been previously performed in this [2] and other active volcanoes, using different geochemical [32,33] and geophysical [34,35] parameters, but with the same finalities. A common finding from these studies is that, during active and passive degassing, these natural systems never attain real equilibria following pseudo-random processes that can be interpreted using statistical approaches.

The fluctuating CO_2 flux signal (natural daily deviation) recorded in 2019 at Stromboli, together with the other monitored parameters, could be the key for the prediction of paroxysmal events. Further related studies on Stromboli, compared with other similar volcanic systems, could improve our knowledge of shallow degassing processes and provide insights on their future behaviors.

5. Conclusions

The period 2016–2019 was characterized by an increase in the frequency of volcanic events with respect to the previous periods [10,11] with many major/paroxysmal explosions like those of 3 July and 28 August 2019.

Analyzing this last period of geochemical monitoring from 2016 to 2019, we observed that the acquired data of soil CO_2 fluxes, monitored on the summit crater area, showed increasing values before and in coincidence with the main volcanic events [10,11]. Before this anomalous period, a slow but continuous recharging process over time until 2019, highlighted by the increasing CO_2 soil degassing, was recorded [11]. The CO_2 summit soil degassing processes showed the following three main and peculiar behaviors:

1. A long-lasting modification, characterized by a slow and continuous increase of CO_2 flux, which indicates that the volatiles pressure in the shallow plumbing system increased over time [11];
2. Transient modifications, characterized by abrupt changes of CO_2 degassing rate, indicating many different pulses of new un-degassed magma arriving in the shallow plumbing system;

3. A strong increase of natural daily variation, highlighting drastic changes of the degassing style just few months before the major paroxysmal events, indicating a strong disequilibrium in the delicate input/output degassing balance [2,9].

In conclusion, the acquired geochemical extensive data set showed the evolution of the Stromboli volcano activity toward more and more critic values [9,11,15], announcing the increased probability of effusive eruptions, major explosions and/or paroxysms [11]. In fact, this increased outgassing activity culminated with the major explosion of 25 June 2019, followed by the paroxysmal events of 3 July and 28 August 2019.

On the basis of the increased volcanic activity recorded in the last decade, combined with the progressive increase of the fluids present in the shallow plumbing system of the volcano, we are able to evaluate the possible evolutionary scenarios of Stromboli's activity.

The higher major/paroxysmal events frequency that occurred in the last years affected a lot the volcanic edifice structure, suggesting that we consider the possibility to have more dangerous catastrophic scenarios in the next future, like that which occurred during the 2002–2003 eruption. In fact, the Sciara del Fuoco flank is very instable, and in the recent past, during the 2002 eruption, a mixed aerial–submarine landslides moved to the sea, producing a tsunami with a wave run up of 11 m around the coast, seriously damaging many buildings located close to the sea in the sector closer to the Sciara [36]. Fortunately, in this case, there were no victims or injured because the tsunami occurred in the winter season, with few tourists on the island and with most of the touristic activities closed.

Finally, the high level of volatiles in the surficial plumbing system depicted by our data and the three major/paroxysmal explosions occurred between June and August 2019, suggesting that the occurrence of a new energetic volcanic event could produce the collapse of the instable Sciara del Fuoco, with the possible generation of a dangerous tsunami.

For this reason, Stromboli volcano should always be considered as dangerous, with a high probability of paroxysmal events, and significant attention must be paid until the level of dissolved volatiles in the shallow plumbing system is high.

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