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Increasing Summit Degassing at the Stromboli Volcano and Relationships with Volcanic Activity (2016–2018)

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Abstract: The last increased volcanic activity of the Stromboli volcano, from 2016 to 2018, was characterized by increases in the number and frequency of crater explosions and by episodes of lava overflow. The volcanic activity was monitored utilizing CO_2 soil fluxes acquired from the Stromboli summit area (STR02 station). To better understand the behavior of the shallow plumbing system of the Stromboli volcano in the period of 2016–2018, we utilized a large data set spanning from 2000 to 2018. The data in this last period confirm a long growing trend of CO_2 summit degassing, already observed in the years since 2005 (reaching 23,000 $g \cdot m^{-2} \cdot d^{-1}$). Moreover, within this increasing trend, episodes of sudden and sharp increases in the degassing rate, up to 24.2 $g \cdot m^{-2} \cdot d^{-2}$ were recorded, which are correlated with the observed paroxysmal activity (increased summit explosions and overflow).

Keywords: Stromboli volcano; geochemical monitoring; summit soil; CO_2 degassing; Strombolian activity

1. Introduction

The 916 m-high Stromboli island is the emerged part of a 3000 m-high volcano lying in the north-eastern sector of the Aeolian archipelago, located in the South Tyrrhenian Sea. Erupted products include basaltic andesites, shoshonites, and latite-trachytes (e.g., [1–5]), dated between 200 ka and >100 ka before present, in Strombolicchio and Stromboli, respectively [6].

Stromboli is an open-conduit volcano characterized by an intense and constant degassing, mainly from the active vents (volcanic plume) and secondarily through the soil, both from the crater terrace (located at ≈750 m above sea level (a.s.l.) in the upper portion of the Sciara del Fuoco) and peripheral areas [7]. A thermal aquifer is also present and accessible in the coastal area, showing a quite constant temperature of ≈40 °C [8].

The total output of CO_2 emitted from the entire volcano edifice (416 $t \cdot day^{-1}$) has been estimated by [7], highlighting that the main contribution comes from the summit area (396 $t \cdot day^{-1}$) and that the CO_2 released from the peripheral areas is only around 20 $t \cdot day^{-1}$. Summit degassing is both active (i.e., explosions from the vents) and passive (i.e., plume from the conduit and diffuse soil degassing in the crater area). Peripheral degassing is due to outgassing of dissolved volatiles from the coastal hydrothermal aquifer, and soil degassing controlled by tectonic discontinuities [9].

During normal Strombolian activity, a delicate dynamic balance is established between a deep input of volatiles, magma degassing, and shallow volatile degassing [10].

This intense degassing is fed by a shallow magma reservoir that releases volatiles during both eruptive activity and inter-eruptive periods [11–13], composed of H_2O, CO_2, SO_2, H_2S, HF, and HCl (condensable gases); some non-condensable gases (e.g., He, H_2, N_2, CO, CH_4) are also released. These fluids are continuously released by magma convection in a shallow magma reservoir (1 km), during which ascending less dense gas-rich magma moves upward, replacing the denser degassed magma that sinks downward [14–16].

Geochemical changes between passive degassing and Strombolian explosions suggest that the former is due to gas released from a shallower magma body within the upper conduits, and the latter is driven by CO_2-rich gas bubbles coming from major depths (>4 km) [16].

Geochemical investigations of volcanic systems utilize two types of data, intensive (chemical and isotopic composition of fluids) and extensive (volatile output) parameters that allow for the formation of a valid fluid degassing model, useful in identifying changes in volcanic activity [10,17–22]. Continuous CO_2 monitoring at volcanoes, as is presented here, is an emerging tool in hazards forecasting, which has enormous potential and tremendous societal relevance, as highlighted in several international and multidisciplinary strategy papers (e.g., [7,9,17–25]).

This paper is focused on the study of the increased volcanic activity of Stromboli (2016–2018), monitored utilizing the large data set of CO_2 soil fluxes acquired from 2000–2018 in the Stromboli summit area (STR02 station).

2. Volcanic Activity

Strombolian activity originates when a discrete gas volume (gas slug) upwells along the conduit at a high velocity, with respect to the surrounding mafic magma, and reaches the cooler upper surface of the magma column, promoting its ascent and the explosive release of gas that is accompanied by the ejection of magma clots [26–29].

Normal Strombolian activity is characterized by passive magma degassing alternating with short-term (up to few tens of seconds) 100- to 200-m high scoria-rich jets caused by variable energy explosions every 10–20 min [30–32]. These explosions show a very low Volcanic Explosive Index (VEI), in the range of −6/−3 utilizing the modified VEI scale as suggested by [33] for very small bulk volume deposits, like those of the Kilauea volcano (Halema'uma'u explosions, HMM; VEI: −2/−4). The normal Strombolian activity is occasionally interrupted by explosive events of higher intensity [34,35], defined as paroxysmal (VEI = 0 or 1) or major explosions (VEI = −2 or −1).

The normal Strombolian activity is fed by a high-porphyritic (HP), volatile-poor magma, whereas paroxysmal and major explosions implicate the discharges of low-porphyritic (LP), volatile-rich magma [36–41].

Major explosions are normally grouped in short time periods (1–2 months), during which Strombolian activity is particularly intense (up to five explosions per hour, [31,42]) and a cool crust forms in one of the craters [43,44]. During these periods of intense Strombolian activity and/or effusive activity, soil and plume CO_2 fluxes are high (over 10,000 $g \cdot m^{-2} \cdot d^{-1}$ and ~10,000 tons day^{-1} respectively, as reported by [19]), and frequently associated with lava overspills from the summit craters [35]. In the last 30 years, four effusive eruptions occurred in 1985, 2002–03, 2007, and 2014; they lasted 5, 7, 1, and 3 months, respectively, with two of these (2002–2003 and 2007) accompanied by paroxysmal events

3. Materials and Methods

Continuous soil CO_2 flux at Pizzo sopra la Fossa (Stromboli summit) was measured on an hourly basis by means of an automated accumulation chamber device (West Systems Ltd.). The dynamic accumulation chamber approach is a direct passive method to measure soil CO_2 fluxes in geothermal and volcanic areas. The increase in CO_2 concentration in the accumulation chamber at a known volume adhering to the soil is directly proportional to the CO_2 flux [45–47]. This method, modified and applied by [48,49], is commonly utilized in the scientific community for geochemical monitoring in volcanic areas [7,9,12,18,19,22,24,25,50–60].

The soil CO_2 measurement station (STR02) is composed of a mechanical automated accumulation chamber and an electronic system that manages the measurement cycle, logs the data, and transmits it, as described in [18,22]. Carbon dioxide was measured with a Dräger Polytron IR spectrometer, which operates in the range of 0–9,9999 ppm (precision of ±5 ppm).

Environmental parameters (wind speed and direction, soil and atmospheric temperatures, atmospheric pressure, and soil and atmospheric relative humidity) were acquired at the same time [22].

Acquired data were transmitted to the Civil Protection Advanced Operations Center (COA) at the Stromboli volcano observatory via a WLAN (wide local area network), where through a VPN (virtual private network link), they were sent to the Istituto Nazionale di Geofisica e Vulcanologia (INGV)-Palermo geochemical monitoring center.

4. Summit Soil CO_2 Flux Continuous Monitoring

The volcanic activity of the Stromboli volcano was monitored over the last 20 years utilizing several geophysical and geochemical techniques. This monitoring activity allowed us to evaluate the level of the Strombolian activity and to individuate the changes between Strombolian and effusive activities [8,9,22,23,52,61–63]. The summit soil CO_2 degassing (Pizzo sopra La Fossa) was monitored using the accumulation chamber method at the continuous STR02 station (Figure 1), a part of the geochemical monitoring network installed on the Stromboli volcano. This equipment represents one of the best tools for monitoring the volcanic activity at Stromboli, as inferred by several investigations carried out in the last years [8–10,12,22,63].

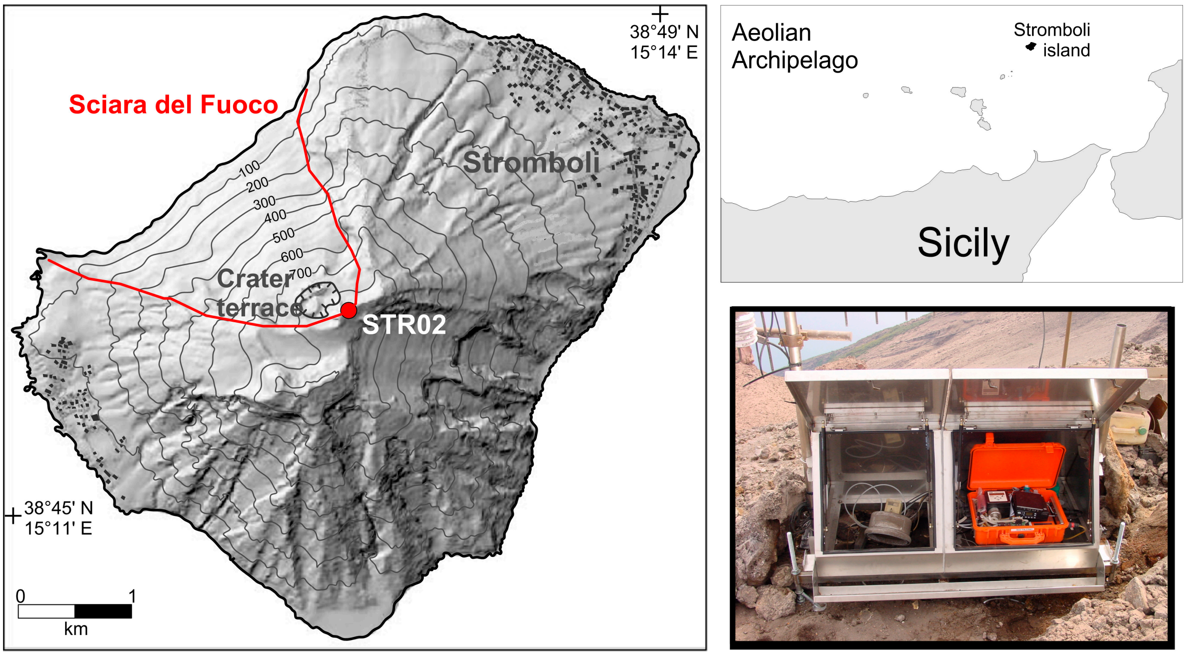

Figure 1. (**a**) Stromboli map with the location of the Stromboli summit area (STR02 station); (**b**) inset of Aeolian archipelago located in the north-east side of the Sicilian coast; (**c**) picture of the STR02 equipment, installed on the summit area (Pizzo sopra La Fossa) of the Stromboli island.

The daily average CO_2 flux of the complete data set, based on 24 measurements per day, acquired from 2000 to 2018, is shown in Figure 2, and the entire period is divided into four sub-periods. The first three periods (five years each) include the three effusive eruptions that occurred in 2002–2003, 2007, and 2014. The last period (January 2016 to February 2018, 26 months) did not include any effusive eruption, but it was characterized by a strong and abrupt increase of summit degassing, coinciding with an increase of explosive activity from the summit craters.

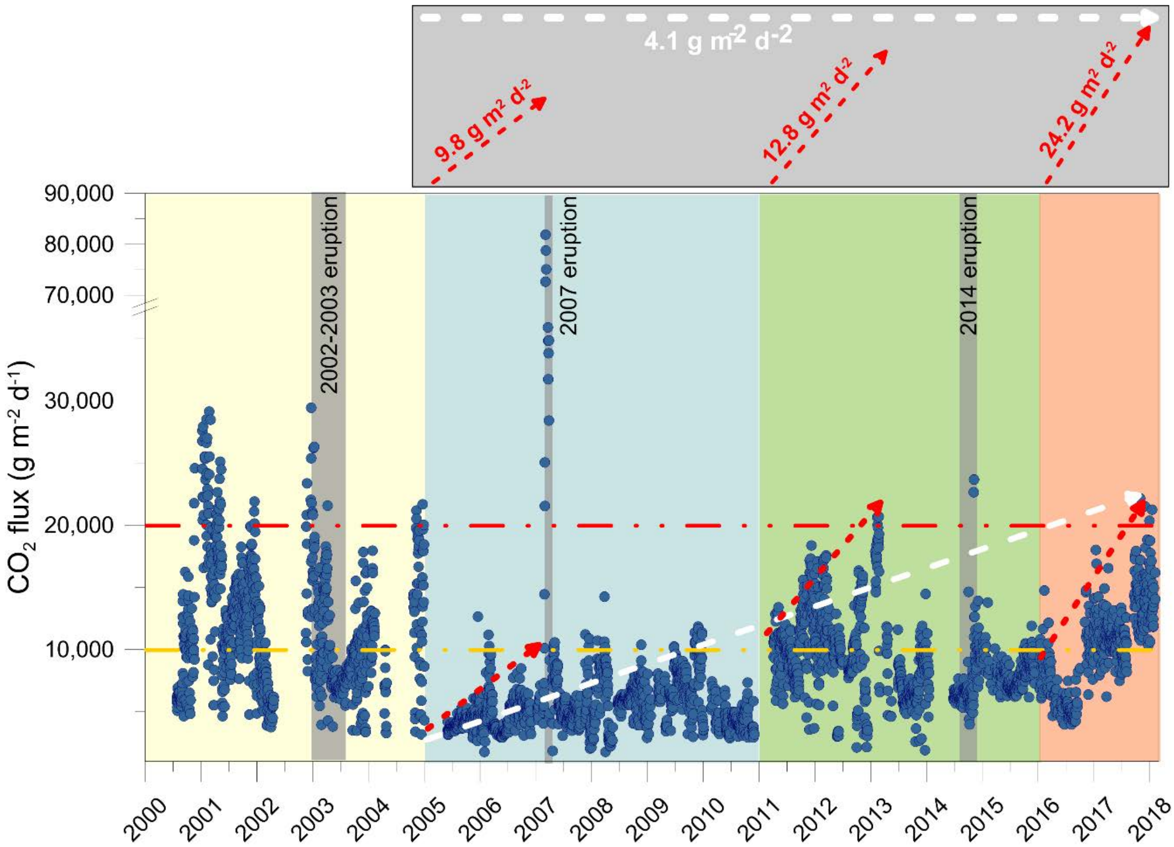

Figure 2. Daily average (24 measurements/day) of CO_2 fluxes at STR02 station, 2000–2018 period. The entire period was grouped into four sub-periods of five years each, except for the last period 2016–2018 (26 months). The first three periods include the effusive eruptions that took place in 2002–2003, 2007, and 2014. The long growing trend of 4.1 $g \cdot m^{-2} \cdot d^{-2}$ (white dashed line, 2005–2018) and the short-term changes of CO_2 degassing (red dashed lines, 9.8, 12.8, and 24.2 $g \cdot m^{-2} \cdot d^{-2}$, respectively) have been included.

Both short-term (2–3 years) and long-term (10–13 years) increases of CO_2 summit degassing, observed in the last 20 years, are linked to direct degassing of shallow magma stored in the open vent of the summit craters [10,18]. In particular, in the first investigated period (2000–2004) the soil flux showed strong degassing (up to thirty thousand $g \cdot m^{-2} \cdot d^{-1}$) with high natural daily variation (NDV), (expressed as normalized standard deviation of 24 daily CO_2 flux measurements; see Inguaggiato et al. 2011 for more details). A long growing trend of daily CO_2 degassing, from 4000 and to 23,000 $g \cdot m^{-2} \cdot d^{-1}$ has been observed in the following sub-periods (from 2005 to 2018, white dashed line in Figure 2) with an increasing average degassing rate of 4.1 $g \cdot m^{-2} \cdot d^{-2}$. 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.

Moreover, we can also observe that the periods prior to the increases in volcanic activity (paroxysms, lava overflows, effusive eruptions) have always been characterized by higher degassing rates, from 2 to 6 times (from 9.8 to 24.2 $g \cdot m^{-2} \cdot d^{-2}$) relative to the long trend average rate of 4.1 $g \cdot m^{-2} \cdot d^{-2}$. These abrupt changes in the degassing rate suggest a large increase in deep volatiles input, which the volcanic system responds to by increasing the rate of shallow degassing. Then, we can observe a greater CO_2 degassing rate increase of 24.2 $g \cdot m^{-2} \cdot d^{-2}$ in the last period, from 2016 to 2018 (6 times higher than the 2005–2015 period), highlighting an abrupt change in the volatile degassing style, which reached up to 24,000 $g \cdot m^{-2} \cdot d^{-1}$ in few months (Figure 2).

For better investigating the behavior of the summit CO_2 fluxes degassing style, during both Strombolian and effusive activities, a statistical approach has been applied to a complete daily average flux data set (2000–2018, Figure 3a,b), considering the selected four sub-periods.

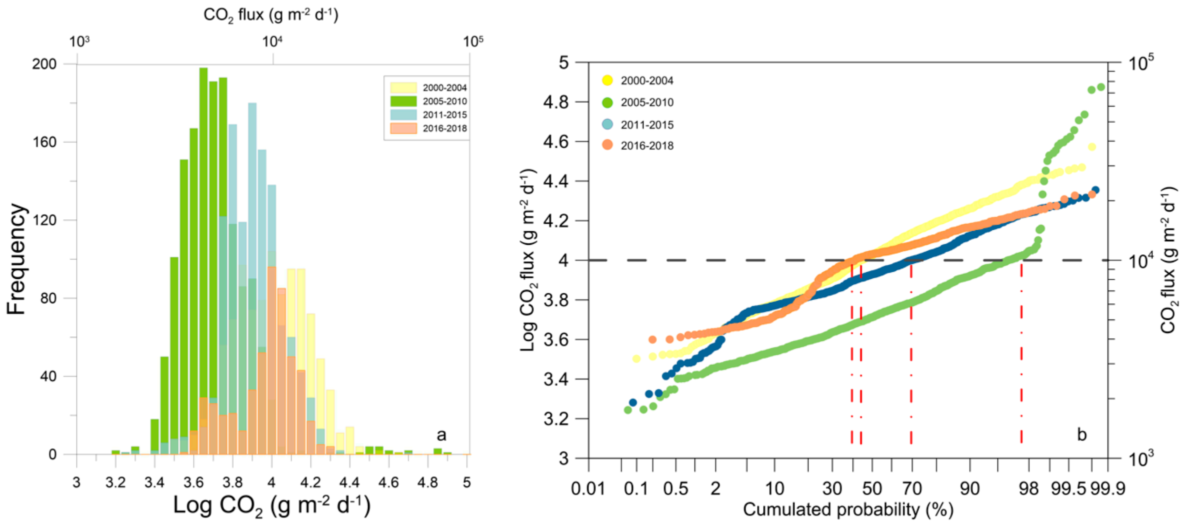

Figure 3. (**a**) Frequency histogram of log CO_2 flux of the four sub-periods (2000–2004, 2005–2010, 2011–2015, 2016–2018); the data shows a quasi-unimodal distribution for the first three periods and bimodal for the last period; (**b**) cumulative probability diagram of log CO_2 flux, the data distribution highlights the different percentage of values over 10,000 g·m^{-2}·d^{-1}. The 2016–2018 sub-period is characterized by the highest percentage (more than 50%) of data over 10,000 g·m^{-2}·d^{-1}) similar to the 2000–2004 period. The other two sub-periods (2002 and 2014) showed only 2% and 30%, above 10,000 g·m^{-2}·d^{-1}, respectively.

The frequency histogram of log CO_2 flux (Figure 3a) shows a similar behavior within sub-periods 1–3 with a quasi-unimodal distribution, although different average values have been recorded in the sub-periods (10,000, 5000, and 9000 g·m^{-2}·d^{-1} for 2002, 2007, and 2014 effusive eruptions periods, respectively). The last period of observation (2016–2018) shows a bimodal distribution, with modal values at 5000 and 14,000 g·m^{-2}·d^{-1}.

Moreover, the cumulative probability diagram of log CO_2 flux (Figure 3b) showed that the 2016–2018 sub-period was dominated by more than 50% of data over 10,000 g·m^{-2}·d^{-1}, like the 2000–2004 period. On the contrary, the other two sub-periods (which include the 2007 and 2014 effusive eruptions) showed 2% and 30% of values above 10,000 g·m^{-2}·d^{-1}, respectively.

5. Discussion and Conclusions

The Stromboli volcano plumbing system is characterized by the continuous refilling of a volatile-rich magma, which produced during the last two thousand years, the peculiar explosive activity called "Strombolian activity" [16,64]. This continuous magma recharge determines a deep volatile input responsible for the increase of the total volatile content inside the shallower plumbing system (located at about 2–4 km depth, [64]), which is partially compensated by the degassing that regulates the delicate dynamic balance between input and output [10].

The last period of observation (2016–2018) highlighted a strong and abrupt increase of soil CO_2 degassing in the summit area of Stromboli, at a CO_2 flux increase rate of 24.2 g·m^{-2}·d^{-2}. This high flux rate was accompanied by an increase of energy and frequency of explosions from 26 July to 01 December 2018, and by the rising of the magma level and consequent lava overflow from the summit vents (Figure 4).

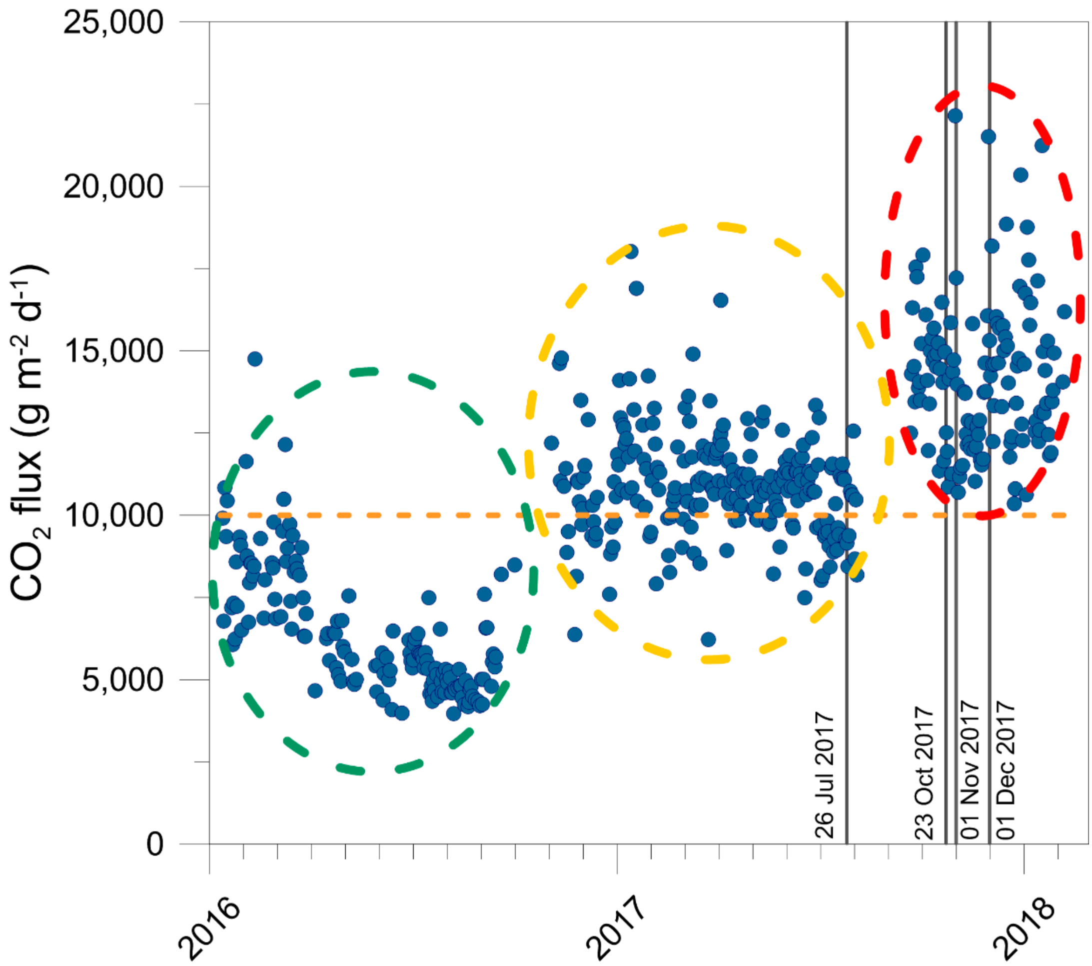

Figure 4. Daily averages (24 measurements/day) of CO_2 fluxes at STR02 station of 2016–2018 period. A strong and sharp increase of soil CO_2 flux is evident: two clear increased degassing families have been recognized (yellow and red dashed circle).

The large data set of summit CO_2 soil degassing, recorded from 2000 to 2018, allowed us to validate the degassing geochemical model formulated by [10] and gave us the opportunity to characterize, from the geochemical viewpoint, the transition between Strombolian and effusive activity.

The study of the cumulative CO_2 flux made it possible to better identify the abrupt slope changes in the summit degassing, highlighting the changes in the degassing styles (Figure 5a). In particular, six main inflection points, marked with dashed red lines, have been recognized from 2005 to 2018, that indicate transient modifications of the shallow system. These inflection points are: (a) in 2007, marking the onset of the 2007 eruption; (b) in 2011 and 2013, identifying the lead-up to the 2014 eruption; (c) in 2015, 2016, and 2017, suggesting the onset of a new critical phase of increased volcanic activity. The significantly large continuous increasing trend of CO_2 flux has been inferred from a monthly average of CO_2 fluxes (Figure 5b, white dashed arrow), which indicates a long-lasting modification of the shallow plumbing system pressure as already hypothesized by [9]. In particular, during the 2007–2013 period, a contemporaneous increase of CO_2 partial pressure in the thermal aquifer and peripheral soil CO_2 degassing corroborate the soil CO_2 fluxes increases recorded at the summit of the volcano. This simultaneous and extended volatile increases support the thesis of a continuous process of pressurization of the shallow plumbing system that affects all the surficial fluid manifestations of the entire volcanic edifice [9].

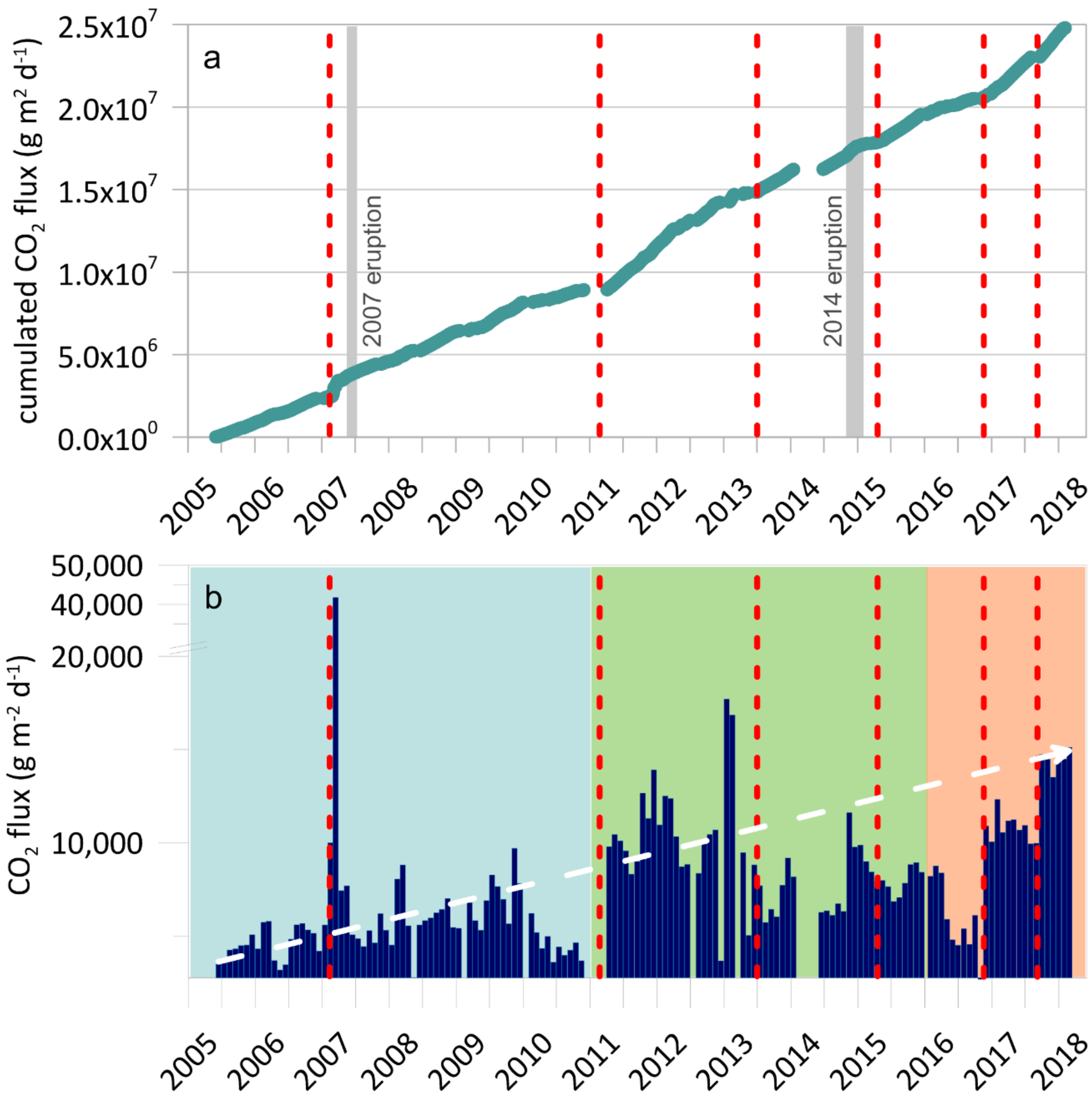

Figure 5. (**a**) Cumulative CO_2 flux vs. time, the inflection points marked with dashed red lines indicate the abrupt changes of degassing style (transient modification); (**b**) monthly average of CO_2 fluxes at STR02 station, the significant large continuous increasing trend of CO_2 flux is evident (white dashed arrow) that indicates a long-lasting modification of the pressure of the shallow plumbing system.

The sketch map of the Stromboli volcano (Figure 6) summarizes and characterizes the main stages of volcanic activity that have been observed at Stromboli over the last 20 years.

In particular we observe:

(a) A highly pressurized shallow plumbing system during the period 2000–2004, inferred from high diffuse CO_2 degassing that culminated in the effusive eruption of 2002–2003 that lasted seven months;

(b) A less pressurized shallow plumbing system during the period 2005–2010, inferred from low diffuse CO_2 degassing and by a very short effusive eruption period that occurred in 2007 and lasted only one month;

(c) A continuous refilling of deep volatiles, starting in 2005, which lead to a new phase (2011–2015), characterized by a constant increase of shallow CO_2 degassing, which culminated in the 2014 effusive eruption that lasted 4 months;

(d) Finally, the 2016–2018 period, characterized by an abrupt increase of shallow CO_2 degassing, which has restored the presence of a very high volatile content in the shallow plumbing system, reaching CO_2 flux values similar to those observed in the 2000–2004 period.

This most recent behavior suggests a new critical phase of degassing, in the delicate dynamic balance between input and output of fluids. This interpretation is well corroborated by the strongly increased volcanic activity recorded, in terms of both frequency and energy, of crater explosions and magma overflow.

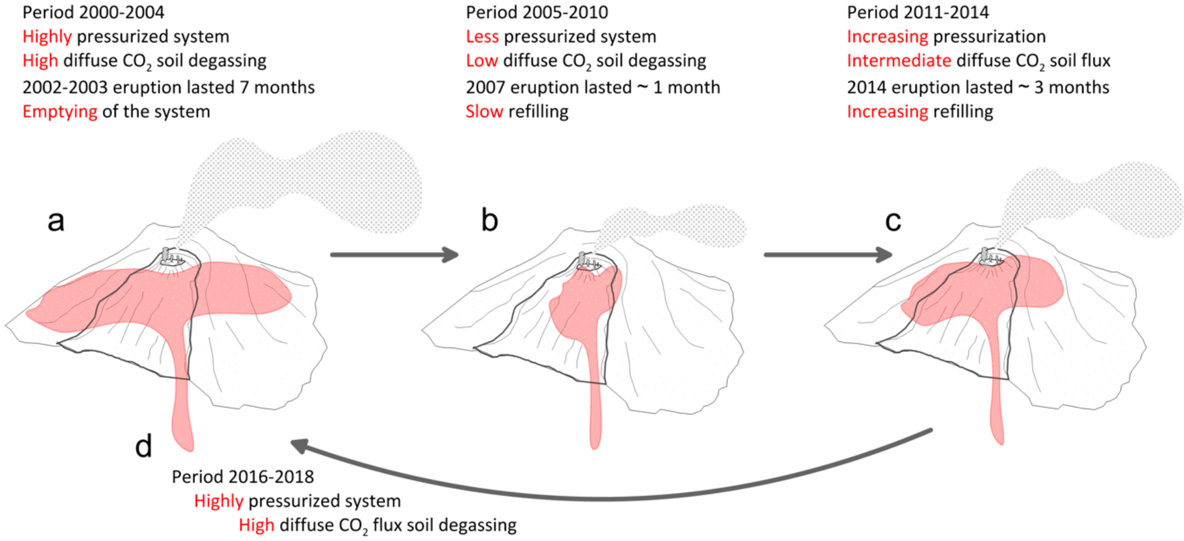

Figure 6. Conceptual sketch map of Stromboli and extent of affected magmatic volatiles–surficial fluids interaction zone (pink regions), showing the four main stages of volcanic activity inferred from its CO_2 degassing behavior.

Author Contributions: Conceptualization, S.I.; interpretation: S.I. and F.V.; Data aquisition, F.V. and L.C.; Data curation, M.C. and L.C.; Graphical editing: M.C.; Writing—original draft preparation, S.I. with minor contribution of F.V. (paragraph 3) and M.C. (paragraph 1 and 2); Writing—review and editing S.I.

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Conflicts of Interest: The authors declare no conflicts of interest.

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