

Magma Supply Dynamics at Mt. Etna (Italy) Inferred from Peripheral Soil CO₂ Emissions: Insights into the 2018 Flank Eruption and the 2021 Paroxysmal Activity

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Abstract

Open-conduit volcanoes are characterized by continuous magma supply and persistent degassing, whereas eruptive activity occurs intermittently and is controlled by magma transfer and accumulation processes within the feeding system. At Mt. Etna, temporal variations in peripheral soil CO₂ emissions provide a sensitive tracer of deep magma intrusions and can be used to quantify magma inputs into the feeding system. Here, we analyze soil CO₂ flux measurements between 2016 and 2021 to reconstruct the evolution of magma supply dynamics, focusing on two major eruptive activities: the December 2018 flank eruption and the exceptional paroxysmal activity of 2021. The reconstructed history reveals contrasting magma supply dynamics associated with the two crises. The December 2018 eruption was preceded by several deep magma input episodes and subsequent upward magma transfer during the preceding months, whereas the 2021 crisis followed the largest magma supply anomaly recorded over the last two decades, which developed between May 2020 and February 2021. This exceptional input preceded the February-April 2021 lava-fountain sequence, one of Etna's most energetic eruptive episodes in recent decades. The reconstructed magma dynamics show remarkable agreement with deformation-derived volume changes and independent geodetic, seismological, geophysical and petrological evidence, supporting the effectiveness of peripheral soil CO₂ emissions in tracking magma input and transfer processes within Etna's plumbing system.

Keywords: Volcanic monitoring; Soil CO₂ emissions; Mt. Etna; Magma supply dynamics; Eruptive potential

1. Introduction

The ascent of magma through volcanic feeding systems is commonly accompanied by the exsolution and release of magmatic volatiles. Among these, CO₂ is particularly useful for investigating deep magmatic processes because of its low solubility in basaltic melts, which causes exsolution at significantly higher pressures than H₂O and most

other magmatic volatile species (Dixon, 1995; Papale et al., 2006; Lesne et al., 2011; Edmonds and Wallace, 2017). Once exsolved from ascending magma, CO₂ migrates upward along permeable pathways. During its ascent, CO₂ may either interact to varying extents with the hydrothermal system or ascend without significant interaction before being released through different pathways. These include visible manifestation such as direct discharge in volcanic plumes (e.g., Woitischek et al., 2021; Ericksen et al., 2024) and focused degassing from fumaroles (e.g., Melian, 2021; Augusto et al., 2023; Matias et al., 2024; Federico et al., 2025), or dissolved in groundwater and aquifers (e.g., Marrero-Diaz et al., 2015; De Gregorio et al., 2005; De Gregorio et al., 2011; Takano et al., 2024), volcanic lake (Pérez et al., 2011; Mazot et al., 2014; Jácome Paz et al., 2016; Andrade et al., 2020; Jácome Paz et al., 2026), and submarine emission (e.g., Price and Giovannelli, 2017; Daskalopoulou et al., 2018; De Gregorio et al., 2025) and even concealed emissions in glacier-covered volcanic systems (Ilyinskaya et al., 2018). In addition, massive amounts of CO₂ are released through soil CO₂ emissions, not only in summit and crater areas but also along volcanic flanks, where faults, fractures, and other permeable structures act as preferential pathways for the ascent of deep magmatic gases (Burton et al., 2013; Werner et al., 2019; Fischer and Aiuppa, 2020). Variations in soil CO₂ fluxes may reflect changes in magma supply rates (e.g., De Gregorio et al., 2014) and magma ascent dynamics (e.g., De Gregorio et al., 2012). Consequently, soil CO₂ flux has become an important geochemical parameter for volcano monitoring and has been extensively investigated at numerous active volcanic systems worldwide, including e.g., Campi Flegrei (Cardellini et al., 2017), Vulcano Island (Camarda et al., 2019), Azores Archipelago (Viveiros et al., 2010, 2017), Taal, Philippines (Pérez et al., 2022), Aso, Japan (Morita et al., 2019), Cumbre Vieja volcano, Canary Islands (Padrón et al., 2015) and others, demonstrating the value of soil CO₂ flux measurements for tracking temporal changes in volcanic degassing and unrest. Of particular relevance to the present study, continuous monitoring at Stromboli revealed marked increases in soil CO₂ flux associated with effusive eruptions and variations in shallow magma supply (Inguaggiato et al., 2017, 2021), whereas observations at Japanese volcanoes identified variations related to volcanic tremor and the ascent of fresh magmatic CO₂ (Hernandez et al., 2001; Shimoike et al., 2002; Morita et al., 2019). Changes in soil CO₂ emissions were also observed before the 2011 submarine eruption at El Hierro (Pérez et al., 2012) and during the 2023 seismic crisis at Laguna del Maule, where they contributed, together with independent geophysical evidence, to the interpretation of a shallow magmatic intrusion (Lamberti et al., 2025). While soil CO₂ emissions are predominantly driven by magmatic dynamics, local tectonic structures can also act as preferential pathways, creating an interplay between gas fluxes and regional seismicity. For instance, at Mammoth Mountain (USA), soil CO₂ fluxes have been observed to track seismic swarms and tectonic stress variations (Werner et al., 2014; Lewicki et al., 2021; Hilley et al., 2022). However, in highly active volcanic systems, the purely tectonic signal is often negligible compared to the overwhelming magnitude of the magmatic signal. A prominent example is the major volcanic crisis that began in 2021 at Vulcano Island (Italy), which was characterized by abrupt CO₂ flux increases up to 30 times the local background levels (Di Martino et al., 2022; Inguaggiato et al., 2022; Federico et al., 2023). During this crisis, although the spatial distribution of the anomalous emissions clearly aligned along regional faults – demonstrating that tectonic structures passively guide fluid ascent toward the surface – the massive release of CO₂ was overwhelmingly driven by volcanic unrest rather than tectonic forcing (De Gregorio et al., 2026).

At Mount Etna (Italy), one of the largest natural sources of volcanic CO₂ on Earth, magmatic fluids are released not only from the summit craters but also through extensive peripheral emission areas distributed around the volcano (Burton et al., 2013; Aiuppa et al., 2019; Werner et al., 2019). The magmatic origin of these emissions has been demonstrated by numerous geochemical studies based on helium isotopes (R/Ra) (Allard et al., 1997; Caracausi et al., 2003), and carbon isotopic compositions ($\delta^{13}\text{C}$ -CO₂) (Giammanco et al., 1998; D'Alessandro et al., 1997; Camarda et al., 2012; Giammanco et al., 2017), indicating the ascent of deep magmatic fluids through the feeding system and associated fault networks. Over the last two decades, our research group has carried out systematic and periodic soil CO₂ flux surveys across three peripheral emission areas, building a unique long-term geochemical dataset that has enabled the reconstruction of magma supply dynamics and the estimation of ascending magma volumes.

Following the conceptual framework proposed by Camarda et al. (2012) and De Gregorio and Camarda (2016), this study reconstructs magma supply dynamics at Mount Etna during 2016–2021, a period encompassing two major eruptive activities characterized by contrasting magma supply and discharge regimes: the December 2018 flank eruption and the highly energetic 2021 lava-fountain sequence (Andronico et al., 2021). Soil CO₂ measurements reveal distinct episodes of magma input and accumulation, including phases in which eruptive activity was sustained by previously accumulated surplus magma and others characterized by substantial concurrent input of deep magma. We compare the magma supply dynamics reconstructed from soil CO₂ emissions with independent observations from geodetic, petrological, geophysical, and geochemical studies.

2. Study Area

Mt. Etna is a basaltic stratovolcano located on the eastern coast of Sicily, its location and origin are intimately linked to the complex geodynamic evolution of the central Mediterranean (Doglioni et al., 2001; Pilet et al., 2026). This unique geodynamic framework sustains a long-lived, polybaric magmatic feeding system (Murru et al., 1999; Chiarabba et al., 2000; De Gori et al., 2005; Zhang et al., 2026). Thermobarometric and petrological studies, particularly on clinopyroxene and plagioclase zoning, reveal that magma crystallization occurs continuously from mantle depths to the sub-surface, with preferential stagnation and mixing at major crustal and lithological discontinuities (Giacomoni et al., 2014; Mollo et al., 2015). Within this vertical column, geodetic, geophysical, and geochemical data outline a plumbing system characterized by two principal ponding zones. The deep ponding zone, located at approximately 15–20 km b.s.l. (Chiarabba et al., 2000), represents the main region of mantle-derived mafic magma replenishment and early crystallization. This depth range is broadly consistent with clinopyroxene crystallization pressures of 600–400 MPa, corresponding approximately to 23–15 km depth (Giacomoni et al., 2016). Above this reservoir, magma may temporarily pond at around 10 km b.s.l., where interactions between ascending mafic inputs and resident, more evolved magma can occur (Murru et al., 1999; Chiarabba et al., 2000; De Gori et al., 2005; Viccaro et al., 2006). The intermediate ponding zone is located at approximately 3–5 km b.s.l. and represents a critical domain for magma storage, differentiation, volatile accumulation, and subsequent transfer toward the shallow feeding system (Murru et al., 1999; Chiarabba et al., 2000; De Gori et al., 2005; Palano et al., 2017). Magma storage within this intermediate depth range is likely favoured by neutral buoyancy between the magma and the surrounding rocks (Palano et al., 2017). Finally, a shallow ponding zone is located within the volcanic edifice, at approximately 3 km beneath the summit craters, corresponding roughly to sea level. This uppermost portion of the plumbing system consists of small, transient storage bodies and conduits that facilitate the final transfer of magma toward the summit craters and commonly feed short-term eruptive activity (Murru et al., 1999; Chiarabba et al., 2000; De Gori et al., 2005; Palano et al., 2017). The periodic transfer of these volatile-rich magmas through these storage zones and the subsequent exsolution of deep-seated, poorly soluble gases act as the primary drivers of system pressurization, ultimately controlling the transition between steady-state passive degassing and energetic eruptive activity (Spilliaert et al., 2006; Moretti et al., 2017). The eruptive behavior of Mt. Etna is highly variable, encompassing persistent passive degassing, frequent summit activity – ranging from mild Strombolian explosions to violent paroxysmal episodes – and flank eruptions. The summit area currently comprises the Voragine (VOR), Bocca Nuova (BN), North-East Crater (NEC), South-East Crater (SEC) and the New South-East Crater (NSEC). Since its formation, the NSEC has become the principal center of summit activity, generating most of Etna's recent lava fountains and ash emissions, including the intense eruptive sequences that characterized 2021 (Andronico et al., 2021). The volcanic edifice is affected by several active tectonic structures among these, the Pernicana Fault on the northeastern flank represents one of the main pathways for the ascent of deep fluids (Neri et al., 2004; Federico et al., 2011; Corsaro et al., 2013). This study focuses on three peripheral emission areas of Mt. Etna: Paternò (PT), located on the southwestern flank of the volcano, Zafferana-Santa Venerina (ZV) on the southeastern flank, and Vena-Presa (VP) along the Pernicana Fault on the northeastern flank (Fig. 1). These areas were selected because previous investigations demonstrated their sensitivity to variations in deep magmatic fluids. Specifically, long-term geochemical monitoring and isotopic analyses – including the carbon isotopic composition of CO₂ and anomalous noble gas signatures, particularly high ³He/⁴He ratios – have clearly evidenced the arrival and persistent release of deep-seated magmatic gases in these peripheral sectors (Allard, 1997; D'Alessandro et al., 1997; Caracausi et al., 2003). The PT and ZV sectors cover approximately 45 km² and 40 km², respectively, whereas the VP monitoring area is restricted to a narrow sector of the Pernicana Fault system. Within PT and ZV surveyed areas, the measurement points are distributed roughly evenly and are defined by a measurement grid with a mean spacing of 600 m. In the PT area, the grid consists of 68 points surrounding the town of Paternò, which is located 23 km from the central craters (Fig. 1). This area is characterized by contacts between outcrops of sedimentary formations and volcanic lavas of the Mongibello Antico and Recente Units (Romano et al., 1979).

Furthermore, three mud volcanoes in this area discharge large amounts of gases with high CO₂ contents (D'Alessandro et al., 1995; Chiodini et al., 1996). The ZV area contains a grid of 65 measurement points surrounding the towns of Santa Venerina and Zafferana Etnea, located 15 km from the central craters (Fig. 1). The volcanic terrains of the Mongibello Recente Unit outcropping in this sector are dissected by north-northwest to south-southeast normal faults (Borgia et al., 1992; Barreca et al., 2013) which provide high-permeability pathways for fluid ascent. In the VP area, the network includes 6 closely spaced sites specifically targeting the degassing dynamics along the active Pernicana Fault. Between January 2016 and December 2021, 48 geochemical surveys were carried out in each of the three investigated sectors, providing a detailed record of soil CO₂ emissions.

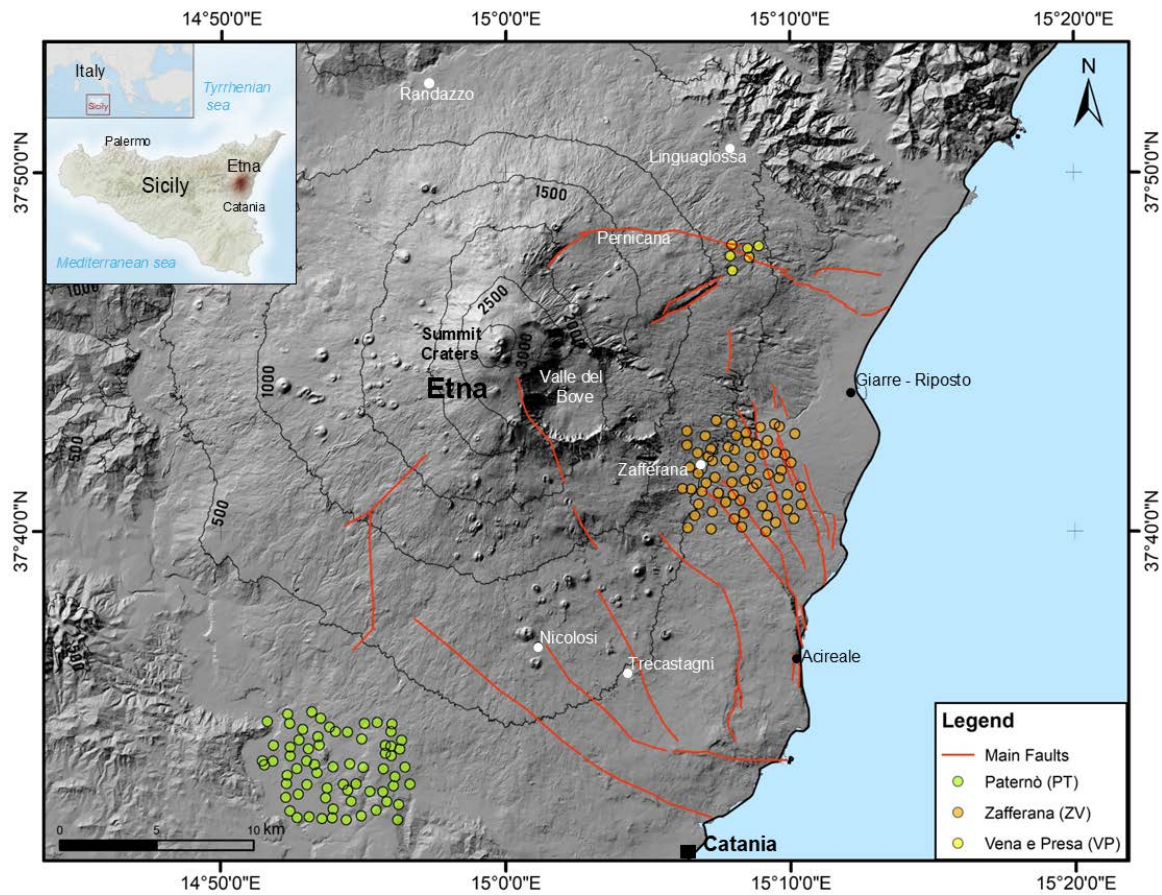


Figure 1. Digital elevation model (DEM) of Mt. Etna, Sicily, showing the spatial distribution of the measurement points belonging to the Paternò (PT, green), Zafferana (ZV, orange), Vena and Presa (VP, yellow) areas. The main tectonic faults are represented by red lines from Barreca et al. (2013). The inset indicates the geographical location of Mt. Etna within Sicily, Southern Italy.

3. Methods

3.1 Soil CO₂ Flux Measurements

Soil CO₂ flux was measured using the dynamic concentration method described by Camarda et al. (2006). This technique is based on measuring the CO₂ concentration in a mixture of air and soil gas generated inside a probe inserted 50 cm below the ground surface. The gas mixture is produced by applying a slight negative pressure with a pump operating at constant flow rate, and CO₂ concentration is measured in-situ by an infrared gas analyzer. After a short equilibration time, generally less than 1 min, the gas mixture reaches a stable value, referred to as the dynamic concentration, which is proportional to the soil CO₂ flux. The relationship between dynamic concentration and flux was established experimentally under controlled laboratory conditions by repeated measurements on soils with known and constant CO₂ fluxes over a wide range of permeability values representative of natural conditions (Camarda et al., 2006).

3.2 Computation of Total Amount of Magmatic CO₂ Emissions and Eruptive Potential

The methodology adopted in this study follows the approach proposed by Camarda et al. (2012) and subsequently integrated by De Gregorio and Camarda (2016). The method is based on long-term soil CO₂ flux measurements performed in the two peripheral areas of PT and ZV, located on the southwestern and eastern flanks of Mt. Etna, respectively. As a first step, the raw soil CO₂ flux data are filtered to remove the influence of atmospheric air

temperature using regression analysis. Since the filtered soil CO₂ fluxes represent a mixture of CO₂ from different sources – specifically, organic CO₂ and CO₂ of deep volcanic origin – it is necessary to separate these components. To isolate the deep magmatic CO₂ contribution, a statistical approach using normal probability plots (PPs) is applied, separately to each area, to identify three distinct data populations: organic background, mixed and deep magmatic.

The mean value is then multiplied by the specific area affected by deep CO₂ emission, which is dynamically determined by the percentage of measurement points belonging to the mixed and magmatic populations during each campaign. This combination yields the total amount of deep magmatic CO₂ emitted per day (t d⁻¹). The resulting time series of deep magmatic soil CO₂ emissions is then analyzed to identify anomalous degassing episodes. Each episode is represented by a peak in the emission signal, defined as the portion of the signal exceeding the site-specific background threshold determined from the inflection points of the corresponding probability plots (960 t d⁻¹ for PT and 470 t d⁻¹ for ZV; values from De Gregorio and Camarda, 2016). Based on their temporal occurrence, these peaks are classified as synchronous, when they are recorded simultaneously in both the PT and ZV areas, or asynchronous, when they are recorded only in the ZV area (Fig. 2). According to Camarda et al. (2012), synchronous peaks reflect episodes of magma transfer in the deep portion of the feeding system (18-10 km b.s.l.). Conversely, asynchronous peaks, recorded only in the ZV area, indicate magma migration toward the intermediate portion of the feeding system (10-3 km b.s.l.). For each peak, the total mass of excess CO₂ released during the anomalous degassing episode is calculated by integrating the area of the peak above the corresponding background threshold. The estimated CO₂ mass is subsequently converted into the mass of ascending magma using the formulation proposed by Harris and Rose (1996). The calculation is based on Henry's law, which relates the equilibrium dissolved CO₂ mole fraction to the equilibrium CO₂ pressure through the Henry constant. The Henry constant for two transfer depths is obtained from the solubility model of Shishkina et al. (2010) and is then used to determine the mass of ascending magma required to dissolve the total CO₂. Subsequently, the volume of degassing magma is calculated from the magma mass by considering the density and the crystallinity of the hawaiite. This procedure provides an estimate of the magma volume directly involved in the degassing process. Since the calculation is based only on the fraction of CO₂ released through soil CO₂ emission, the resulting magma volumes represent partial magma volumes (VPM). Following De Gregorio and Camarda (2016), these partial volumes are converted into equivalent total magma volumes (VTM) through a conversion factor derived from the proportional relationship between VPM and the erupted magma volume (VEP) over a complete recharge-eruption cycle. Once the VTM progressively entering the system is quantified, the Eruptive Potential (EP) curve over time is reconstructed by continuously subtracting the volume of magma progressively emitted during eruptive events (VEP) from the cumulative volume of intruded surplus magma (VTM). Therefore, the resulting EP curve reflects the temporal variation of the amount of surplus magma stored within the feeding system that might be potentially erupt.

3.3 Standardization of Soil CO₂ Flux and EP Time Series

Unlike the PT and ZV sectors, the limited number of sites along the Pernicana Fault (VP) prevents a reliable estimate of the daily magmatic CO₂ output; therefore, soil CO₂ flux variations were evaluated using Z-scores to highlight values potentially associated with episodes of magma supply. The Z-score was calculated by subtracting the mean of the entire investigated time series from each observed value and dividing the resulting difference by the corresponding standard deviation. The mean and standard deviation were calculated over the entire 2005-2021 time series. The use of Z-scores is particularly useful because it standardizes the signal relative to its mean and standard deviation, thereby allowing anomalous variations to be identified directly and compared over time according to their statistical significance. Increasing positive Z-scores in the VP area indicate progressively enhanced soil CO₂ emissions associated with magma supply, with values exceeding +1 σ used to identify periods of high magma supply. The same standardization was applied to the EP time series to express the estimated magma volume stored within the plumbing system in terms of its deviation from the mean value.

4. Results

A comprehensive characterization of magma dynamics requires quantifying both magma supply and the cumulative volume of magma stored within the feeding system. While magmatic CO₂ emissions provide a quantitative record

of magma supply, the cumulative magma volume constrains the state of the feeding system and the amount of magma potentially available for future eruptions.

4.1 Soil and Magmatic CO₂ Emissions

This section presents the temporal evolution of daily amount of magmatic CO₂ emitted in the PT and ZV peripheral areas, together with the temporal evolution of soil CO₂ flux measured along the Pernicana Fault VP during the 2016-2021 period. In the PT and ZV monitoring areas, the daily amount of magmatic CO₂ emitted was reconstructed from soil CO₂ flux measurements, providing a quantitative record of variations in magma supply within the Etna feeding system (Fig. 2). The PT area exhibits a series of major positive anomalies throughout the investigated period (red peaks in Fig. 2). These anomalies are synchronous with those recorded in the ZV area and occurred in 2016, late 2017, late 2018, 2019 followed by a pronounced increase between mid-2020 and early 2021. This latter anomaly represents the largest emissive event recorded over the entire 2005-2021 dataset, reaching values

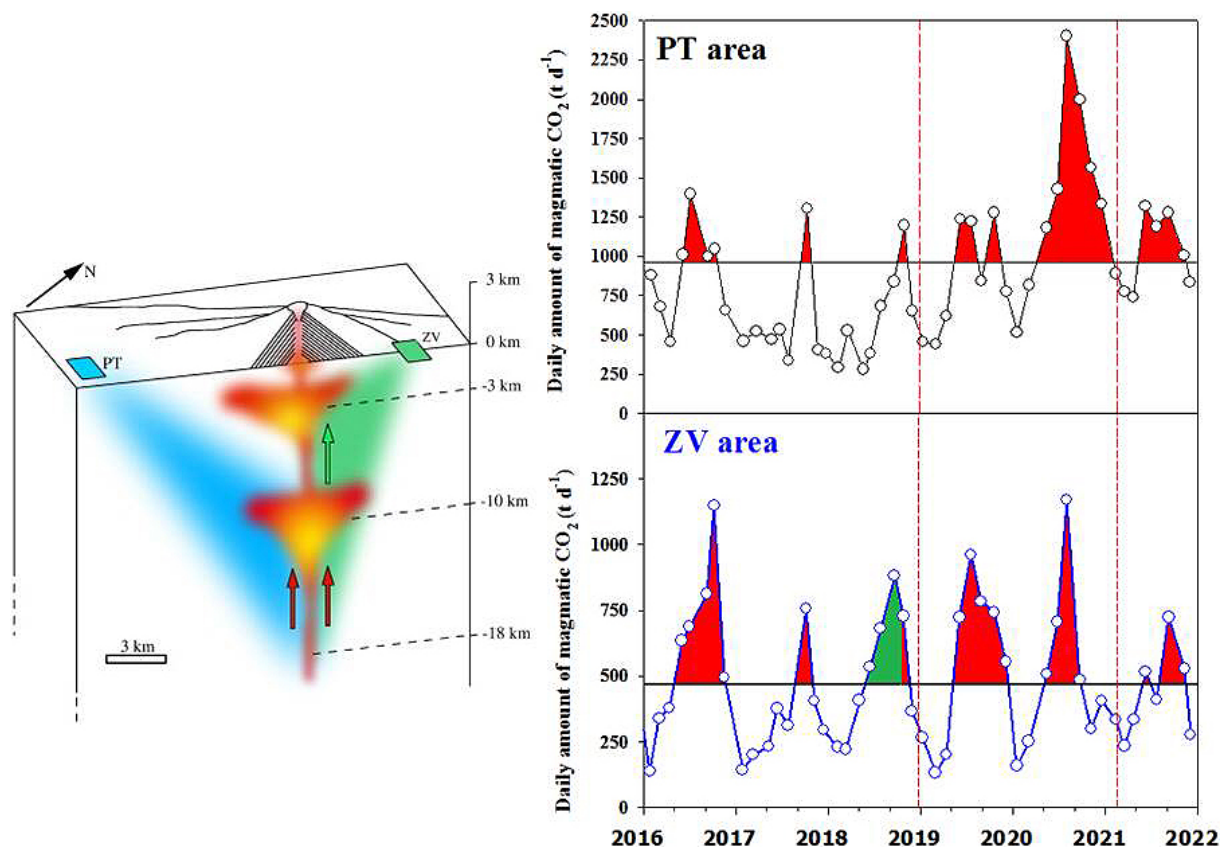


Figure 2. Three-dimensional sketch of the Mt. Etna plumbing system (left) and temporal evolution of the daily amount of magmatic CO₂ emitted in the Paternò (PT) and Zafferana-Santa Venerina (ZV) monitoring areas between 2016 and 2021 (right). In the sketch, equal horizontal and vertical scales highlight the locations of the monitoring areas relative to the main magma storage zones, whose positions and lateral and vertical extents are consistent with Murru et al. (1999), Chiarabba et al. (2000), and De Gori et al. (2005). The blue and green regions represent the inferred feeding zones of magmatic soil CO₂ emissions in the PT and ZV areas, respectively. Red arrows indicate magma supply from 18 to 10 km b.s.l., which produces synchronous CO₂ emission peaks in both monitoring areas, whereas the green arrow indicates magma transfer from 10 to 3 km b.s.l., associated with an asynchronous increase recorded only in the ZV area, according to the conceptual model of Camarda et al. (2012). In the time series, horizontal lines indicate the threshold values used to identify periods of enhanced CO₂ emissions. Red peaks represent synchronous increases associated with magma supply to the deep feeding system, whereas the green peak represents an asynchronous increase related to magma transfer toward the intermediate storage system. Vertical dashed lines indicate the onsets of the December 2018 eruption and the February 2021 paroxysmal sequence.

exceeding 2400 t d^{-1} of magmatic CO_2 and indicating a major magma intrusion into the deep portions of the plumbing system. The anomaly culminated a few weeks before the onset of the February 2021 lava-fountain sequence. A last synchronous peak was recorded during the second half of 2021. The ZV area shows a pattern consistent with that observed at PT, with the same synchronous peaks although with generally lower amplitudes (maximum values of $\sim 1100\text{--}1200 \text{ t d}^{-1}$). In addition to the synchronous peaks, a single prominent asynchronous peak (green) was recorded at the ZV area between June and November 2018. According to the conceptual model proposed by Camarda et al. (2012), this peak reflects magma migration from the deep feeding system toward intermediate reservoirs.

Interestingly, the asynchronous peak was immediately followed by a synchronous peak, indicating that magma transfer toward shallower levels was rapidly accompanied by a renewed deep magma supply. Along the Pernicana Fault (VP), soil CO_2 flux measurements are reported as z-score (Fig. 3). The VP z-score time series remained close to background levels until mid-2018. From June 2018 onward, a progressive increasing trend developed, culminating in the first days of January 2019, when z-scores exceeded the $+1\sigma$ threshold. Elevated values persisted throughout most of 2019 and 2020, whereas z-scores returned close to background levels after the February 2021 eruptive sequence before showing a moderate increase again during the second half of 2021.

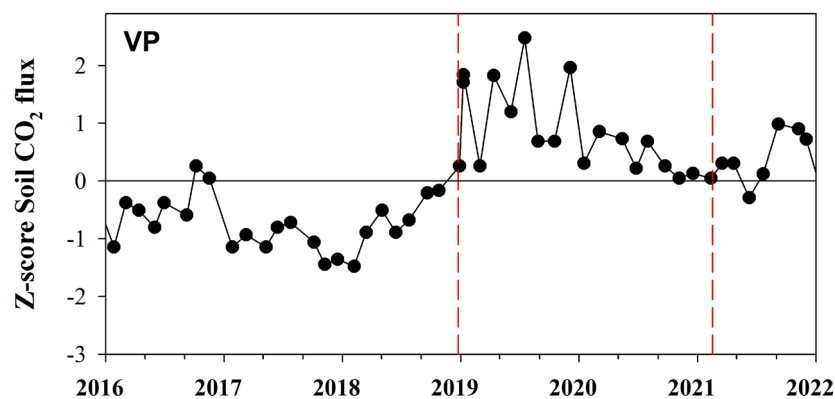


Figure 3. Temporal evolution of soil CO_2 flux z-score values measured along the Pernicana Fault (VP area) between 2016 and 2021. The central horizontal line at 0 represents the mean value, while the vertical dashed lines indicate the onset of the December 2018 eruption and the February 2021 paroxysmal sequence.

4.2 Cumulative Magma Volume Estimates

The cumulative magma volume stored within a volcanic feeding system reflects the balance between magma recharge and magma withdrawal during eruptive activity. Consequently, temporal variations in magma accumulation provide important information on the state of the feeding system and on the amount of magma potentially available for future eruptions. Figure 4 shows the evolution of the cumulative volume of magma stored within the Etna feeding system between 2005 and 2021 reconstructed using three independent approaches. Although the main focus of this study is the 2016–2021 period, the reconstruction was extended back to 2005 in order to place the recent eruptive activity within the broader context of the long-term evolution of the Etna feeding system. The longer time window allows magma accumulation and withdrawal processes to be evaluated over a longer timeframe, providing a reference framework against which the magnitude and significance of the 2016–2021 variations can be assessed.

The first approach (blue curve in Fig. 4) is based on the computation of magma volume from soil CO_2 emission data, following the model proposed by De Gregorio and Camarda (2016). This curve for the period spanning 2005 to 2015 is taken directly from the reconstruction proposed by De Gregorio and Camarda (2016). For the subsequent period, from 2016 onwards, the curve has been updated and reconstructed in the present study by rigorously applying the exact same methodology. As described above, the excess magmatic CO_2 released during each anomaly is converted into total magma volume using a magma-volatile balance approach and then cumulatively integrated over time. According to De Gregorio and Camarda (2016), the resulting magma volume does not represent the total amount of magma stored within the feeding system. Instead, it represents the cumulative volume of surplus magma, i.e., the magma supplied in excess of the long-term background input required to sustain the ordinary activity of

the volcano. This surplus magma progressively accumulates within the feeding system and constitutes the fraction that can potentially be mobilized during future eruptions. Accordingly, De Gregorio and Camarda (2016) referred to this cumulative surplus magma volume as the Eruptive Potential, which provides an estimate of the magma volume potentially available for future eruptive activity at any given time. The second reconstruction (black curve in Fig. 4) was specifically reconstructed in this study following the conceptual approach proposed by Calvari and Nunnari (2022), who suggested that the long-term evolution of the Etna feeding system can be approximated by a nearly constant magma supply rate of about $0.8 \text{ m}^3 \text{ s}^{-1}$. Under this assumption, magma continuously enters the feeding system and progressively accumulates during quiescent periods, whereas eruptive episodes produce a reduction of the stored magma volume. Accordingly, the temporal evolution of magma accumulation was reconstructed by continuously adding the magma supplied at a constant rate. The resulting curve therefore represents the theoretical evolution of magma stored within the feeding system under the assumption of a steady magma input and variable eruptive output. In both approaches, erupted magma volumes were progressively subtracted from the curves through time. During periods characterized by simultaneous magma supply and eruptive activity, the reconstructed values represent the net balance between magma input and magma output over the considered time interval. Consequently, the curves reflect the residual magma volume remaining within the feeding system after accounting for both processes. The erupted volumes used in both reconstructions were derived from the dataset compiled by Calvari and Nunnari (2022), who integrated satellite thermal observations, lava discharge rates and volcanological measurements to quantify magma output during the recent eruptive activity of Mt. Etna. The third reconstruction (green curve in Fig. 4) is based on the geodetic dataset presented by Palano et al. (2024). To facilitate direct comparison with the other cumulative time series, which all begin in 2005, the cumulative magma volume variations were recalculated by setting the reference value to zero at the beginning of 2005. The resulting cumulative curve was therefore reconstructed in this study using the magma volume changes estimated by Palano et al. (2024). In their work, magma accumulation was quantified through geodetic modelling of successive inflation and deflation phases associated with the pressurization and depressurization of magmatic reservoirs beneath the volcano. The geodetic modelling identifies deformation sources located within the shallow and intermediate portion of the Etna plumbing system, with inflation sources distributed in the 4-9 km depth range and deflation sources in the 3-6 km depth range. Unlike the previous two reconstructions, this curve directly represents cumulative magma volume changes inferred from ground deformation measurements and therefore does not rely on erupted magma volumes derived from volcanological datasets. Instead, both magma accumulation and withdrawal are independently constrained by geodetic observations. The comparison

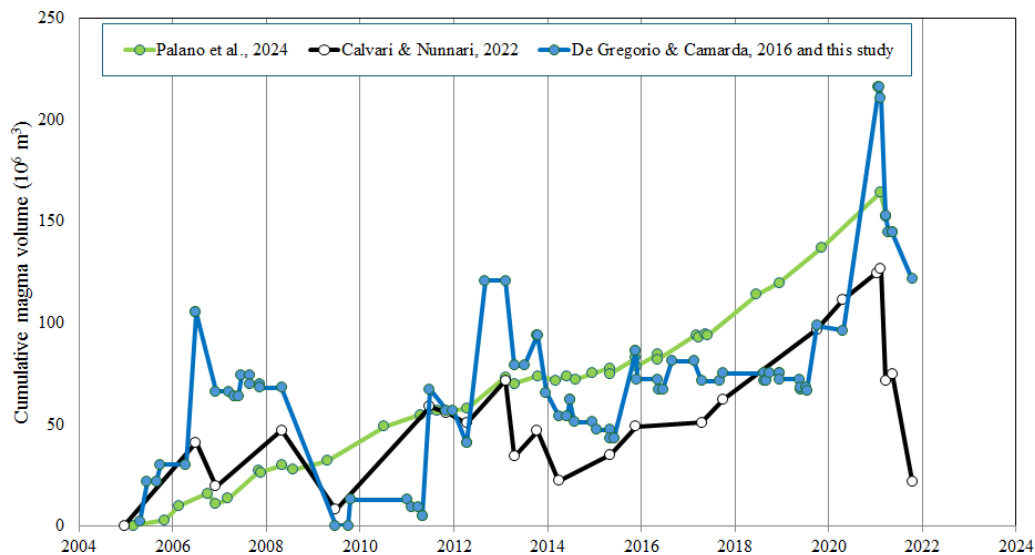


Figure 4. Comparison among the cumulative magma volumes reconstructed from soil CO_2 emissions according to De Gregorio and Camarda 2016 with independent estimates derived from volcanological and geodetic observations. The blue curve represents the cumulative volumes reconstructed from soil CO_2 emissions, the green curve corresponds to the cumulative volume variations inferred from geodetic observations by Palano et al. (2024). The black curve was reconstructed in this study by applying the continuous magma supply-rate model proposed by Calvari and Nunnari (2022).

among these three independently derived reconstructions provides a unique opportunity to evaluate the consistency of the inferred magma dynamics over nearly two decades of volcanic activity. Although derived from different datasets and based on different assumptions, the three reconstructions show a broadly comparable general evolution and yield magma-volume estimates of a similar order of magnitude, while displaying differences related to their specific methodological frameworks. In particular, the reconstruction of Calvari and Nunnari (2022) includes fewer data points because it assumes a continuous magma recharge rate, with changes in the cumulative magma budget occurring only in association with eruptive events.

Conversely, the reconstructions based on soil CO₂ emissions and the geodetic model of Palano et al. (2024) contain a larger number of data points because they describe the magma budget through both episodic magma supply events and magma discharge associated with eruptive activity. These reconstructions therefore show a more articulated temporal evolution, characterized by successive increases and decreases in cumulative magma volume. Thus, the different density and temporal distribution of the data points primarily reflect the distinct conceptual frameworks used to reconstruct magma supply and withdrawal. However, while the cumulative volumes reconstructed from soil CO₂ emissions and those inferred from the geodetic model of Palano et al. (2024) are characterized by a comparable number and temporal distribution of data points, the former curve exhibits significantly larger amplitude oscillations than geodetic one.

This difference can be explained by the fact that the geodetic approach inherently provides minimum estimates for both magma input (during inflation phases) and magma output (during deflation phases). As noted by Palano et al. (2024), their calculated volumes must be considered lower bounds because the model assumes an isotropic elastic half-space medium with a Poisson's ratio of 0.25. Furthermore, concerning the deflation phases specifically, geodetically modeled volume losses are typically much lower than the actual erupted magma volumes (often 1 to 8 times smaller). This severe underestimation during eruptive discharges is primarily driven by the high compressibility of magma – which is strongly controlled by the exsolution of deep volatile phases like CO₂. Additionally, the two methods sample different portions of the feeding system. The soil CO₂ emissions recorded in peripheral areas are sensitive to deep magma intrusions because CO₂ exsolves at high pressure and can migrate toward the surface from depths exceeding 18 km below sea level. In contrast, the deformation sources identified by Palano et al. (2024) are mainly located within intermediate reservoirs beneath the summit area, generally between about 4 and 9 km below sea level. Consequently, soil CO₂ emissions are able to capture the full magnitude of the magma supply dynamics occurring in the deeper portions of the feeding system.

Furthermore, the cumulative volumes of magma calculated using our geochemical approach are generally larger than those estimated by Calvari and Nunnari (2022), whose evaluations are based on expected values derived from a constant average magma supply rate. While these models provide valuable estimations over long timescales, might not capture the short-term dynamics of sudden magma input events equally well. In contrast, our methodology dynamically quantifies the actual surplus of magma progressively entering the system. This allows us to track real-time increases in magma supply rates and short-term variations much more effectively. Finally, and importantly, all three methods reach their maximum values immediately preceding the paroxysmal events of February 2021. This convergence testifies to the extraordinary magnitude of the magma supply that fueled this sequence, an event distinctly recorded across all independent approaches.

5. Discussion

5.1 Eruptive Activity and Magma Supply Dynamic During 2016-2021

The period investigated in this study (2016-2021) encompasses markedly different phases of activity at Mt. Etna. After a period of relatively moderate activity, the NSEC reactivated during February-April 2017, producing Strombolian explosions, lava flows and lava fountains associated with renewed magma transfer within the feeding system (Fig. 5). Volcanic activity subsequently culminated in the 24-27 December 2018 flank eruption, a short-lived eruptive episode characterized by the opening of an eruptive fissure on the eastern flank of the NSEC, lava effusion within the Valle del Bove, intense seismicity and the occurrence of a Mw 4.9 earthquake on 26 December 2018. Following the 2018 eruption, the volcano entered a new phase of reactivation that culminated in the exceptionally energetic paroxysmal activity of 2021, when more than fifty lava fountains occurred between February and October. These events produced some of the highest eruption columns, thermal radiative power values and magma discharge rates

observed at Etna in recent decades and represent one of the most intense eruptive crises documented in the recent history of the volcano (Andronico et al., 2021; Marchese et al., 2021; Corsaro et al., 2024).

The succession of eruptive phases described above reflects significant variations in magma supply dynamics and storage conditions within the feeding system. These changes are reflected in the temporal evolution of the EP (Fig. 5), which provides a quantitative measure of the surplus magma potentially available for future eruptive activity and offers a useful framework for interpreting how the balance between magma supply and magma output evolved over time. Figure 5 shows the evolution of EP during the 2016-2021 period, expressed as absolute magma volume (10^6 m^3) on the left axis and as the corresponding standardized EP values (z-scores) on the right axis, together with the eruptive activity.

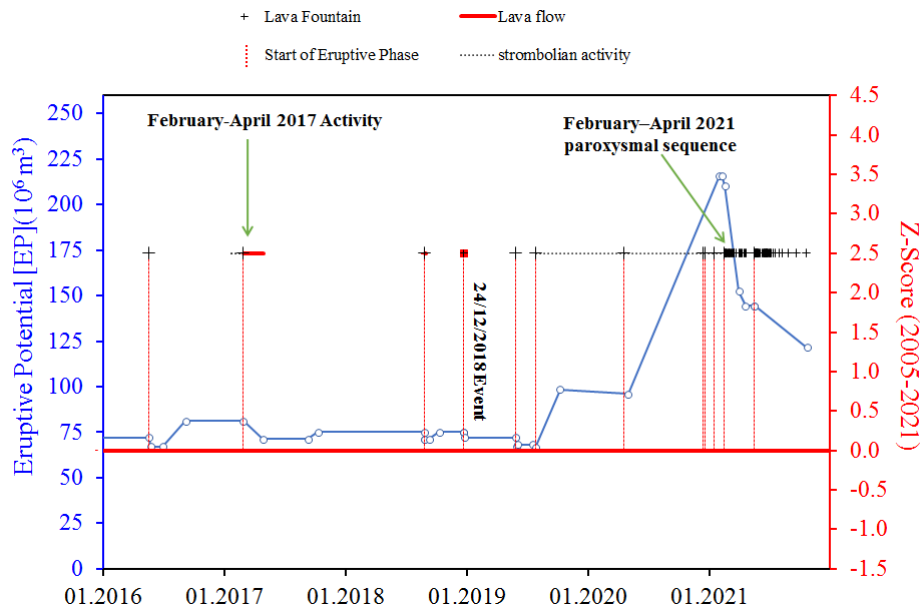


Figure 5. Temporal evolution of Eruptive Potential (EP) between 2016 and 2021. The left axis reports the cumulative volume of surplus magma corresponding to Eruptive potential whereas the right axis shows the corresponding standardized values (z-scores) calculated relative to the 2005-2021 reference period using the datasets reported by Camarda et al. (2012) and De Gregorio and Camarda (2016), together with the new data presented in this study. After several years characterized by EP values close to the long-term average, a pronounced increase occurred during 2020-2021, before the February-April 2021 paroxysmal sequence.

The z-scores were calculated using the complete EP dataset available for the 2005-2021 period. During most of the investigated period, EP remained close to the zero z-score level, indicating that the volume of surplus magma stored within the deep feeding system remained close to the average value characterizing the 2005-2021 interval. Within this framework, z-score values near zero do not imply the absence of magma available for eruption; rather, they indicate that the system contains a magma volume comparable to that typically present during its recent evolution. Under these conditions, even relatively modest magma inputs may be sufficient to trigger eruptive activity, as observed during the February-March 2017 eruptive phase. It is noteworthy that EP remained close to the zero z-score level for several years, this suggests the long-term persistence of magma within the deeper portions of the feeding system, which may subsequently be transferred toward intermediate and shallow storage levels without producing substantial variations in EP. The December 2018 eruption developed within this context. As will be discussed in the following section, this eruptive crisis was primarily characterized by magma transfer within intermediate and shallow portions of the feeding system rather than by a major increase in deep magma input. Consequently, its precursor phase is only partially expressed by the EP curve. A significant change in the behavior of the system became evident from mid-2019 onward, when EP started to increase progressively. This phase coincided with the gradual reactivation of summit activity, initially characterized by Strombolian explosions and increasing eruptive unrest.

The rate of EP increase became markedly higher during 2020, indicating a greater estimated magma supply per unit time and producing the largest positive EP value of the investigated period. This phase of unusually high inferred

magma input occurred before the February–April 2021 lava–fountain sequence. This suggests that the exceptionally energetic paroxysmal activity of 2021 was preceded by an unusually large magma input into the plumbing system. The occurrence of seventeen lava fountains between February and April 2021 coincided with the highest eruptive potential of the entire time series, indicating that magma accumulation reached a critical level before the onset of the paroxysmal sequence. These observations highlight two different patterns of the Etna feeding system during the investigated period: the 2018 eruption developed after a prolonged persistence of magma at depth and was mainly controlled by magma transfer toward shallower levels, whereas the 2021 paroxysmal activities were preceded by the largest deep magma accumulation recorded in the EP time series.

The observations presented above indicate that the magma supply dynamics during the 2018 and 2021 eruptive crises evolved through a succession of distinct stages involving deep magma supply, magma transfer through the feeding system and magma withdrawal. Based on the temporal evolution of EP and the reconstructed magma supply dynamics, we propose the conceptual model shown in Fig. 6. The model summarizes the successive stages of magma supply, magma transfer and magma withdrawal during the 2018 and 2021 eruptive periods and provides the interpretative framework for integrating the soil CO₂ record with independent geophysical, geochemical and petrological observations.

5.2 The December 2018 Eruptive Episode

The December 2018 eruption occurred from 24 to 27 December following the gradual reactivation of summit activity during summer and autumn 2018. On 24 December, thousands of shallow seismic events and ash emissions from the summit craters preceded the opening of an eruptive fissure on the eastern flank of the New South-East Crater. The fissure propagated downslope for approximately 2 km and fed lava flows within the Valle del Bove. Although the eruption was short-lived and produced a relatively limited lava-flow field, it was accompanied by an intense seismic swarm and culminated in the Mw 4.9 earthquake that occurred on 26 December. This eruptive episode represented the culmination of a prolonged phase of magma accumulation and transfer within the Etna feeding system (Alparone et al., 2020; Giampiccolo et al., 2020).

The temporal evolution of magmatic CO₂ emissions provides a coherent reconstruction of the magma dynamics preceding the eruption. Between 2016 and early 2018, several synchronous anomalies were recorded in both the PT and ZV sectors (Fig. 2). According to the conceptual framework adopted in this study, synchronous anomalies reflect magma inputs into the deeper portions of the feeding system, approximately between 18 and 10 km b.s.l. These observations indicate repeated episodes of deep magma supply during the two years preceding the eruption shown by phase 1 in Fig. 6.

A significant change occurred during summer 2018, when a pronounced anomaly developed exclusively in the ZV sector. This asynchronous signal, which persisted from June to October 2018, suggests the progressive transfer of magma from the deep domain toward intermediate storage zones located between approximately 3–5 km b.s.l. The onset of this anomaly marks a transition from deep magma accumulation to upward magma migration within the plumbing system (Phase 2 in Fig. 6)

Additional evidence of shallow magma transfer was provided by the VP z-scores soil CO₂ flux time series. From June 2018 onward, the standardized z-scores of soil CO₂ flux measured along the Pernicana Fault showed a progressive increasing trend, culminating in the first days of January 2019, when values exceeded the $+1\sigma$ threshold (Fig. 3). This pattern is consistent with a progressive increase in the contribution of deeply derived magmatic CO₂ to diffuse soil emissions along the fault, suggesting continued magma and fluid transfer through the shallow feeding system before and across the December 2018 eruptive phase (Phase 3 in Fig. 6). Importantly, this shallow transfer was accompanied by renewed magma input into the deep plumbing system, as indicated by the synchronous peak that immediately followed the asynchronous one. The close succession of these signals therefore suggests that Phase 3 (Fig. 6) involved the simultaneous activation of both the deep and shallow portions of a highly pressurized feeding system immediately before the onset of the December 2018 flank eruption.

The chronology reconstructed from soil CO₂ emissions closely matches the evolution independently inferred from geodetic observations. Borzì et al. (2020) showed that a major reactivation of the plumbing system began in June 2017, when magma replenishment induced prolonged inflation of a reservoir located at approximately 7.2 km b.s.l. According to their model, magma migration toward shallower levels started in June 2018, leading to pressurization of a reservoir located at approximately 5.1 km b.s.l., while a further upward migration phase began during November 2018.

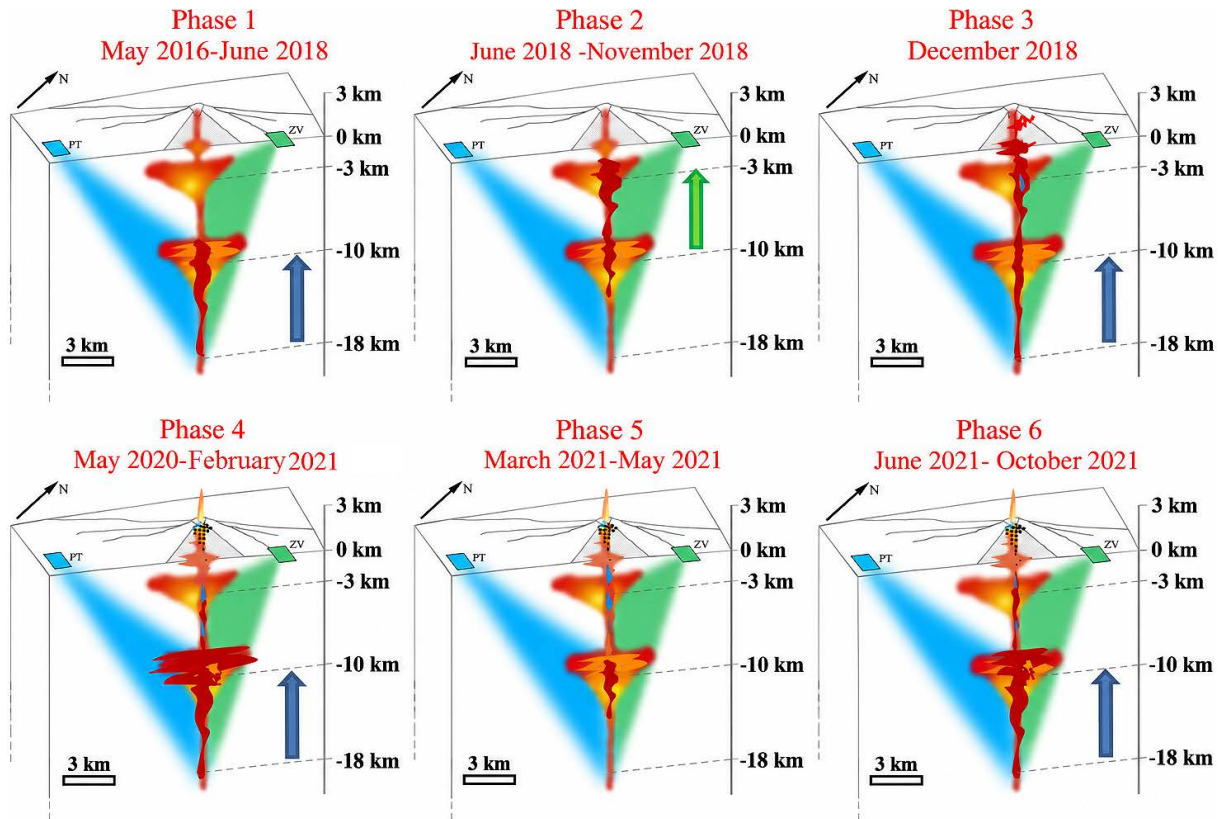


Figure 6. Conceptual model of magma supply dynamics during the two major eruptive crises of the 2016-2021 period at Mt. Etna. The base of the panels is a three-dimensional sketch of the Mt. Etna feeding system. In this sketch, the horizontal and vertical scales are the same to highlight the locations of the study areas (PT blue square and ZV green square) with respect to the main magma storage zones. The placement of these storage zones and their lateral and vertical extensions are in agreement with Murru et al. (1999), Chiarabba et al. (2000), and De Gori et al. (2005). The color gradation of the magma bodies from yellow to red provides a qualitative indication of relative magma residence, with red representing newly supplied magma and yellow representing magma that has resided longer within the feeding system. The panel summarize the phases of deep magma supply, magma transfer through the feeding system, and magma withdrawal associated with the December 2018 flank eruption (Phases 1-3) and the 2020-2021 paroxysmal activity (Phases 4-6). The model is derived from the temporal evolution of Eruptive Potential (EP) and the reconstructed magma supply dynamics inferred from soil CO₂ emissions. Blue and green areas indicate the inferred feeding zones of magmatic soil flux in the PT and ZV areas, respectively. Light blue arrows: Deep magma supply from 18 to 10 km b.s.l. Green arrows: Upward magma transfer through the intermediate feeding system from 10 to 3 km b.s.l.

The timing of these geodetically inferred transfer processes is remarkably consistent with the sequence of CO₂ anomalies observed in the ZV and VP sectors. The interpretation of progressive magma migration during 2018 is further supported by the seismic analysis of Firetto Carlino et al. (2022), who identified a phase of increasing pressurization within the intermediate storage system beginning in June 2018 and culminating shortly before the December eruption. The onset of this pressurization phase closely coincides with the asynchronous CO₂ anomaly recorded in the ZV area, suggesting that both datasets capture the same process of magma transfer from deep reservoirs toward intermediate storage levels. Independent geochemical and petrological evidence further supports the magma transfer sequence reconstructed from soil CO₂ emissions. Paonita et al. (2021) demonstrated that the December 2018 eruption was preceded by the arrival of a new volatile-rich primitive magma batch into the Etna plumbing system. Variations in helium isotopes, noble gas compositions and diffuse CO₂ emissions indicate enhanced deep magma input from 2017 through summer 2018, followed by rapid transfer of magmatic fluids toward shallower portions of the feeding system from June 2018 to November 2018. Complementary evidence is provided by Correale et al. (2024), who investigated melt inclusions hosted in olivine crystals from the 2018 products and

showed that the erupted magma resulted from interaction between newly supplied primitive magma and resident magma stored at shallower levels. Their results indicate progressive magma recharge, mixing and upward transfer through multiple storage zones before eruption. The chronology inferred from these geochemical and petrological observations is therefore fully consistent with the sequence reconstructed from soil CO₂ emissions.

The final stage of the activity is constrained by the joint inversion of gravity and deformation data performed by Chauhan et al. (2020). Their results indicate that the December 2018 eruption was primarily fed by magma withdrawal from shallow storage zones and lateral transport into the eruptive dyke. This interpretation supports the view that the final pre-eruptive phase was dominated by magma redistribution within the upper portions of the plumbing system rather than by direct ascent from deep reservoirs.

A complementary perspective is provided by the seismological study of Alparone et al. (2020), which showed that dyke emplacement strongly interacted with the eastern flank fault system and promoted fault reactivation and flank deformation. Together with the gravity and deformation results of Chauhan et al. (2020), these observations indicate that a substantial fraction of the energy accumulated during the 2018 unrest was accommodated by dyke intrusion, fault activation and deformation of the volcanic edifice rather than by magma eruption at the surface.

Overall, the remarkable agreement among soil CO₂ emissions, geodetic observations, seismic data, geochemical tracers and petrological evidence supports a coherent interpretation of the December 2018 eruption. The eruptive episode was preceded by prolonged magma recharge at depth, followed by progressive transfer toward intermediate and shallow storage levels during 2018, and culminated in dyke emplacement and lateral magma propagation immediately before eruption. The soil CO₂ record successfully reconstructs the entire sequence of magma migration, from deep recharge to shallow transfer, highlighting its effectiveness as a tracer of magma dynamics within the Etna plumbing system.

5.3 The 2020-2021 Paroxysmal Activity

A second exceptional eruptive phase occurred in 2021, when the NSEC produced one of the most energetic paroxysmal sequences observed at Mt. Etna in recent decades (Andronico et al., 2021; Marchese et al., 2021; Corsaro et al., 2024). Following transitional activity during December 2020 and January 2021, a sequence of 17 lava fountains took place between 16 February and 1 April 2021. These events generated lava fountains up to approximately 1000 m high, eruption columns reaching 10-11 km a.s.l., extensive tephra fallout, lava flows and pyroclastic density currents. Ash fallout repeatedly affected inhabited areas and, during some episodes, caused temporary closure of Catania airport (Andronico et al., 2021; Marchese et al., 2021; Corsaro et al., 2024). Satellite observations further revealed that several of these paroxysms produced some of the highest thermal radiative power values ever recorded at Etna, with the 31 March-1 April event reaching approximately 14 GW (Marchese et al., 2021). A second paroxysmal sequence (SEQ2) subsequently developed between May and October 2021 and was followed by two additional paroxysms in February 2022.

The temporal evolution of EP provides important insights into the magma supply processes that sustained this exceptional eruptive activity. During the first months of 2020, EP remained relatively stable and close to its long-term average value. Beginning in May 2020, however, EP started to increase continuously, reaching the highest values of the entire investigated period before the onset of the February-April 2021 paroxysmal sequence. This interval corresponds to Phase 4 of the conceptual model (Fig. 6), which is interpreted as a period of sustained deep magma supply and progressive accumulation within the feeding system prior to the onset of the paroxysmal activity. This increase corresponds to the accumulation of approximately $125 \times 10^6 \text{ m}^3$ of surplus magma within the feeding system and implies a magma supply rate of about $5 \text{ m}^3 \text{ s}^{-1}$, substantially higher than the long-term average value of approximately $0.8 \text{ m}^3 \text{ s}^{-1}$.

A valuable test of the magma dynamics inferred from EP is provided by the petrological monitoring of the 2020-2021 eruptive activity (Corsaro and Miraglia, 2022; Corsaro et al., 2024). Corsaro et al. (2024) identified two main eruptive sequences separated by a period of reduced magma supply and limited eruptive activity: SEQ1 (13 December 2020-1 April 2021) and SEQ2 (19 May-23 October 2021). Their results show that magma evolution during both sequences was controlled by mixing between an evolved magma residing in the shallow SEC reservoir and a more primitive magma supplied from deeper levels of the plumbing system. During SEQ1, the contribution of primitive magma progressively increased from the transitional activity of December 2020-January 2021 to the climax of the lava-fountain sequence, reaching its maximum in late February 2021 when the most primitive

magma compositions of the entire eruptive activity were observed (Corsaro and Miraglia, 2022). The temporal correspondence between the EP increase and the petrological evolution is particularly remarkable. The period characterized by progressive magma accumulation inferred from soil CO₂ emissions closely overlaps the interval during which petrological observations document increasing contributions of primitive magma. Moreover, EP continued to increase during the initial stages of SEQ1, indicating that magma input exceeded magma output despite the onset of intense eruptive activity. This observation suggests that magma supply and magma discharge occurred simultaneously and that the February–April 2021 paroxysms were sustained by a major deep magma input affecting the entire plumbing system. Following the climax of SEQ1, EP decreased markedly between March and May 2021. This decline occurred in the absence of significant new magma accumulation and is interpreted as the result of magma withdrawal associated with repeated lava fountains and lava effusion. This interval corresponds to Phase 5 of the conceptual model (Fig. 6), during which the deep magma recharge diminished and magma withdrawal from the intermediate and shallow reservoirs exceeded the replenishment rate, leading to a progressive decrease in eruptive potential. This interpretation is fully consistent with the petrological reconstruction proposed by Corsaro et al. (2024), who identified the March–May 2021 interval as a phase of reduced magma supply separating the two main paroxysmal sequences. During this period, the contribution of primitive magma progressively decreased, while fractional crystallization became increasingly important.

Petrological observations indicate that a renewed phase of magma replenishment began during summer 2021. Increasing contributions of primitive magma were recorded throughout SEQ2, culminating in late August when the most primitive compositions of the second sequence were observed (Corsaro and Miraglia, 2022; Corsaro et al., 2024). Within the conceptual model proposed in Fig. 6, Phase 6 marks the onset of a renewed deep magma supply. Although this process is not reflected by the EP evolution owing to the simultaneous high magma discharge, it is clearly indicated by the renewed increase in daily magmatic CO₂ emissions (Fig. 2), which exhibits a distinct anomaly starting on June 2021 and cover the same period, indicating continued magma supply from depth.

Overall, the remarkable agreement between EP variations and the petrological evolution reconstructed by Corsaro et al. (2024) indicates that the 2020–2021 eruptive activity was controlled by alternating phases of magma supply, magma transfer and magma withdrawal.

Additional evidence for an unusually deep magma recharge process is provided by the clinopyroxene thermobarometric study of Mollo et al. (2022). Their modelling of clinopyroxene crystals erupted during the February–April 2021 lava fountains indicates that these paroxysms were fed by injections of hotter magma originating from pressures of approximately 170–480 MPa, interpreted as corresponding to depths of ~11–15 km. Clinopyroxene zoning records a vertically extensive plumbing system affected by repeated injections of fresh magma, magma mixing, and crystal recycling. A key difference with respect to the 2011–2012 lava fountains are that the 2021 eruptions were supplied by hotter magmas derived from deeper levels of the plumbing system, implying a greater contribution of primitive magma to the eruptive feeding system. These observations are consistent with the large EP anomaly reconstructed prior to SEQ1 and support the interpretation that the 2021 paroxysms were fed by a recharge event affecting a substantial portion of the feeding system rather than by the simple drainage of a shallow reservoirs.

Complementary evidence is provided by MacDonald et al. (2024), who identified repeated episodes of mafic rejuvenation and crystal mush remobilization during the same eruptive sequence. Their results indicate that shallow reservoirs were repeatedly replenished by hotter and more primitive magma batches, providing direct evidence of recharge and remobilization processes within the feeding system. Taken together, these observations indicate that the February–April 2021 paroxysms involved magma transfer through a large portion of the Etna plumbing system and support the interpretation that the exceptional EP anomaly preceding SEQ1 reflects a major recharge event rather than the simple evacuation of a shallow magma reservoir. The interpretation of a system-wide recharge event is further supported by the 4D seismic tomography study of De Gori et al. (2021), which documented renewed magma accumulation beneath the summit area between 2019 and 2021. Their results indicate that the Etna plumbing system underwent substantial re-pressurization following the 2018 intrusion and suggest the presence of large volumes of magma stored within a transcrustal reservoir system capable of sustaining eruptive activity for years. The exceptional EP anomaly identified in this study therefore appears consistent with an extensive recharge process affecting multiple levels of the feeding system.

A broader framework for interpreting these observations is provided by Giuffrida et al. (2023), who summarized a decade of multidisciplinary investigations at Mt. Etna and highlighted the key role of primitive magma recharge in controlling the 2021 eruptive activity. According to their synthesis, the first months of 2021 were characterized by activation of the most primitive magmatic environments of the Etna plumbing system and by rapid transfer of mafic

magma toward intermediate and shallow storage levels. The overall agreement among soil CO₂ emissions, petrological observations, seismic tomography and geodetic studies strongly supports the interpretation that the 2021 paroxysmal activity was the surface expression of a major recharge event affecting a large portion of the Etna feeding system.

These observations demonstrate that soil CO₂ emissions provide a robust tool for tracking magma dynamics and accumulation processes and reconstructing the evolution of eruptive potential prior to major eruptive crises. The close correspondence between the CO₂-derived EP record and independent petrological and geophysical observations indicates that soil CO₂ monitoring can successfully capture both the timing and the magnitude of major magma recharge episodes within the Etna feeding system.

6. Conclusions

Peripheral soil CO₂ emissions allowed us to reconstruct the main magma supply and transfer processes that characterized Mt. Etna during the 2016–2021 period. The reconstructed evolution reveals contrasting dynamics preceding the two major eruptive crises. The December 2018 flank eruption occurred after repeated episodes of deep magma supply and was primarily associated with the progressive transfer of magma already stored within the plumbing system toward intermediate and shallow levels. Conversely, the 2021 paroxysmal activity was preceded by the largest increase in eruptive potential observed during the investigated period, indicating an exceptional phase of deep magma recharge and accumulation within the feeding system. A major outcome of this study is the integration of the soil CO₂-derived reconstruction with multiple independent datasets. The comparison with geodetic observations, seismic data, seismic tomography, geochemical, and petrological evidence reveals a remarkable consistency in the timing and interpretation of the main stages of magma supply and transfer. By combining these different observations within a common interpretative framework, this multidisciplinary approach provides a more comprehensive reconstruction of the evolution of Etna's feeding system than any individual dataset considered separately. These results support the value of long-term peripheral soil CO₂ monitoring for tracking deep magma supply, upward magma transfer, and changes in eruptive potential. When integrated with complementary geophysical, geochemical, and petrological observations, soil CO₂ emissions can contribute to distinguishing eruptive activity driven by new magma recharge from that sustained by the redistribution of magma already stored within the plumbing system.

Data availability statement. The data presented in the current study are available from the corresponding author upon reasonable request.

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References

- Agusto, M., M. C. Lamberti, F. Tassi, F. Carbajal et al. (2023). Eleven-year survey of the magmatic-hydrothermal fluids from Peteroa volcano: identifying precursory signals of the 2018–2019 eruption, *Geochem. Geophys. Geosyst.*, 24, 11, doi:10.1029/2023GC011064.
- Aiuppa, A., T. P. Fischer, T. Plank and P. Bani (2019). CO₂ flux emissions from the Earth's most actively degassing volcanoes, 2005–2015, *Sci. Rep.*, 9, 5442, doi:10.1038/s41598-019-41901-y.
- Allard, P., P. Jean-Baptiste, W. D'Alessandro, F. Parelo et al. (1997). Mantle-derived helium and carbon in groundwaters and gases of Mount Etna, Italy, *Earth Planet. Sci. Lett.*, 148, 3–4, doi:10.1016/S0012-821X(97)00052-6.
- Alparone, S., G. Barberi, A. Bonforte, V. Maiolino et al. (2020). Seismological constraints on the 2018 Mt. Etna (Italy) flank eruption and implications for the flank dynamics of the volcano, *Terra Nova*, 32, 5, 334–344, doi:10.1111/ter.12463.

- Andrade, C., J. V. Cruz, F. Viveiros and R. Coutinho (2020). CO₂ emissions from Fogo intracaldera volcanic lakes (Sao Miguel Island, Acores): A tool for volcanic monitoring, *J. Volcanol. Geotherm. Res.*, 400, 106915, doi:10.1016/j.jvolgeores.2020.106915.
- Andronico, D., A. Cannata, G. Di Grazia and F. Ferrari (2021). The 1986-2021 paroxysmal episodes at the summit craters of Mt. Etna: Insights into volcano dynamics and hazard, *Earth Sci. Rev.*, 220, 103686, doi:10.1016/j.earscirev.2021.103686.
- Barreca, G., A. Bonforte and M. Neri (2013). A pilot GIS database of active faults of Mt. Etna (Sicily): A tool for integrated hazard evaluation, *J. Volcanol. and Geotherm. Res.*, 251, 170-186, doi:10.1016/j.jvolgeores.2012.08.013.
- Borgia, A., L. Ferrari and G. Pasquarè (1992). Importance of gravitational spreading in the tectonic and volcanic evolution of Mount Etna, *Nature*, 357, 6375, 231-235, doi:10.1038/357231a0.
- Borzi, A. M., M. Giuffrida, F. Zuccarello, M. Palano et al. (2020). The Christmas 2018 eruption at Mount Etna: Enlightening how the volcano factory works through a multiparametric inspection, *Geochem. Geophys., Geosyst.*, 21, e2020GC009226, doi:10.1029/2020GC009226.
- Burton, M. R., G. M. Sawyer and D. Granieri (2013). Deep carbon emissions from volcanoes, *Rev. Mineral. Geochem.*, 75, 323-354, doi:10.2138/rmg.2013.75.11.
- Calvari, S. and G. Nunnari (2022). Comparison between automated and manual detection of lava fountains from fixed monitoring thermal cameras at Etna volcano, Italy, *Rem. Sens.*, 14, 2392, doi:10.3390/rs14102392.
- Camarda, M., S. Gurrieri and M. Valenza (2006). CO₂ flux measurements in volcanic areas using the dynamic concentration method: influence of soil permeability, *J. Geophys. Res.*, 111, B05202, doi:10.1029/2005JB003898.
- Camarda, M., S. De Gregorio and S. Gurrieri (2012). Magma-ascent processes during 2005-2009 at Mt Etna inferred by soil CO₂ emissions in peripheral areas of the volcano, *Chem. Geol.*, 330-331, 218-227, doi:10.1016/j.chemgeo.2012.08.024.
- Camarda, M., S. De Gregorio, G. Capasso, R. M. Di Martino, et al. (2019). The Monitoring of Natural Soil CO₂ Emissions: Issues and Perspectives, *Earth Sci. Rev.*, 198, 102928, doi:10.1016/j.earscirev.2019.102928.
- Caracausi, A., R. Favara, S. Giammanco, F. Italiano et al. (2003). Mount Etna: Geochemical signals of magma ascent and unusually extensive plumbing system, *Geophys. Res. Lett.*, 30, 1057, doi:10.1029/2002GL015463.
- Cardellini, C., G. Chiodini, F. Frondini, R. Avino et al. (2017). Monitoring diffuse volcanic degassing during volcanic unrests: the case of Campi Flegrei (Italy), *Sci. Rep.*, 7, 6757, doi:10.1038/s41598-017-06941-2.
- Chauhan, A., F. Cannavò, D. Carbone and F. Greco (2020). Insights into Mount Etna December 2018 eruption from joint inversion of deformation and gravity data, *Geophys. Res. Lett.*, 47, e2020GL087786, doi:10.1029/2020GL087786.
- Chiarabba, C., A. Amato, E. Boschi and F. Barberi (2000). Recent seismicity and tomographic modeling of the Mount Etna plumbing system, *J. Geophys. Res.*, 105, B5, 10923-10938, doi:10.1029/1999JB900427.
- Chiodini, G., W. D'Alessandro and F. Parello (1996). Geochemistry of the gases and of the waters discharged by the mud volcanoes of Paternò, Mt. Etna (Italy), *Bull. Volcanol.*, 58, 51-58.
- Correale, A., R. A. Corsaro, L. Miraglia, A. Paonita et al. (2024). The December 2018 eruption at Etna volcano: a geochemical study on melt and fluid inclusions, *Front. Earth Sci.*, 11, 1122132, doi:10.3389/feart.2023.1122132.
- Corsaro, R. A., V. Di Renzo, S. Distefano, L. Miraglia et al. (2013). Relationship between petrologic processes in the plumbing system of Mt. Etna and the dynamics of the eastern flank from 1995 to 2005, *J. Volcanol. Geotherm. Res.*, 251, 75-89, doi:10.1016/j.jvolgeores.2012.02.010.
- Corsaro, R. A. and L. Miraglia (2022). Near real-time petrologic monitoring on volcanic glass to infer magmatic processes during the February-April 2021 paroxysms of the South-East Crater, Etna, *Front. Earth Sci.*, 10, 828026, doi:10.3389/feart.2022.828026.
- Corsaro, R. A., L. Miraglia, I. Arienzo and V. Di Renzo (2024). The 2020-2022 paroxysmal episodes of the South-East Crater (Mt. Etna): insights into high-frequency eruptive activity from petrological monitoring, *Bull. Volcanol.*, 86, 85, doi:10.1007/s00445-024-01770-4.
- D'Alessandro, W., R. De Domenico, F. Parello and M. Valenza (1995). Geochemical Anomalies in the Gaseous Phase of the Mud Volcanoes of Paternò, Sicily, *Proc. Sci. Meet. Seism. Prot.*, Venice, 12-13 July, 1993, 171-175.
- D'Alessandro, W., S. De Gregorio, G. Dongarrà, S. Gurrieri et al. (1997). Chemical and Isotopic Characterization of the gases of Mount Etna, *J. Volcanol. Geotherm. Res.*, 78, 65-76, doi:10.1016/S0377-0273(97)00003-6.
- Daskalopoulou, K., A. L. Gagliano, S. Calabrese, M. Longo et al. (2018). Gas geochemistry and CO₂ output estimation at the island of Milos, Greece, *J. Volcanol. Geotherm. Res.*, 365, 13-22, doi:10.1016/j.jvolgeores.2018.10.003.
- De Gori, P., C. Chiarabba and D. Patanè (2005). Qp structure of Mt. Etna: constraints for the physics of the plumbing system, *J. Geophys. Res.*, 110, B05303, doi:10.1029/2003JB002875.

- De Gori, P., E. Giampiccolo, O. Cocina, S. Branca et al. (2021). Re-pressurized magma at Mt. Etna, Italy, may feed eruptions for years, *Commun. Earth Environ.*, 2, 1-9, doi:10.1038/s43247-021-00282-9.
- De Gregorio, S., S. Gurrieri and M. Valenza (2005). A PTFE membrane for the in situ extraction of dissolved gases in natural waters: Theory and applications, *Geochem. Geophys. Geosyst.*, 6, 9, Q09005, doi:10.1029/2005GC000947.
- De Gregorio, S., M. Camarda, M. Longo, S. Cappuzzo et al. (2011). Long-term continuous monitoring of dissolved CO₂ in groundwater at Mt. Etna (southern Italy), *Water Res.*, 45, 3005-3011, doi:10.1016/j.watres.2011.03.028.
- De Gregorio, S., M. Camarda, G. Gurrieri and R. Favara (2014). Change in magma supply dynamics identified in observations of soil CO₂ emissions in the summit area of Mt. Etna, *Bull. Volcanol.*, 76, 846, doi:10.1007/s00445-014-0846-2.
- De Gregorio, S. and M. Camarda (2016). A novel approach to estimate the eruptive potential and probability in open conduit volcanoes, *Sci. Rep.*, 6, 30471, doi:10.1038/srep30471.
- De Gregorio, S., M. Camarda, A. Pisciotta and V. Francofonte (2025). Shallow Submarine CO₂ Emissions in Coastal Volcanic Areas Implication for Global Carbon Budget Estimates: The Case of Vulcano Island (Italy), *Environments*, 12, 6, 197, doi:10.3390/environments12060197.
- De Gregorio, S., M. Camarda, G. Capasso, R. M. R. Di Martino et al. (2026). Tectonic Control on Soil CO₂ Emissions in an Active Volcanic System: Insights from Vulcano Island, *Geosciences*, 16, 225, doi:10.3390/geosciences16060225.
- Di Martino, R. M. R., S. Gurrieri, M. Camarda, G. Capasso et al. (2022). Hazardous changes in soil CO₂ emissions at Vulcano, Italy, in 2021, *J. Geophys. Res., Solid Earth*, 127, doi:10.1029/2022JB024516.
- Dixon, J. E., E. M. Stolper and J. R. Holloway (1995). An experimental study of water and carbon dioxide solubilities in mid-ocean ridge basaltic liquids. Part I: Calibration and solubility models, *J. Petrol.*, 36, 6, 1607-1631, doi:10.1093/oxfordjournals.petrology.a037267.
- Dogliani, C., F. Innocenti and G. Mariotti (2001). Why Mt Etna?, *Terra Nova*, 13, 1, 25-31, doi:10.1046/j.1365-3121.2001.00301.x.
- Edmonds, M. and P. J. Wallace (2017). Volatiles and Exsolved Vapor in Volcanic Systems, *Elements*, 13, 1, 29-34, doi:10.2113/gselements.13.1.29.
- Ericksen, J., T. P. Fischer, G. M. Fricke, S. Nowicki et al. (2024). Drone CO₂ measurements during the Tajogaite volcanic eruption, *Atmos. Meas. Tech.*, 17, 4725-4736, doi:10.5194/amt-17-4725-2024.
- Federico, C., M. Camarda, S. De Gregorio and S. Gurrieri (2011). Long-term record of CO₂ degassing along Mt. Etna's flanks and its relationship with magma dynamics and eastern flank instability, *Geochem. Geophys. Geosyst.*, 12, 10, Q10002, doi:10.1029/2011GC003601.
- Federico, C., O. Cocina, S. Gambino, A. Paonita et al. (2023). Inferences on the 2021 ongoing volcanic unrest at Vulcano Island (Italy) through a comprehensive multidisciplinary surveillance network, *Remote Sens.*, 15, 1405, doi:10.3390/rs15051405.
- Federico, C., A. Paonita, R. M. R. Di Martino, S. Bellomo et al. (2025). Geochemistry of La Fossa fumaroles (Vulcano Island, Aeolian Islands) unveils the evolving magmatic sources of the fluid before and during the 2021 unrest, *Chem. Geol.*, 123168, doi:10.1016/j.chemgeo.2025.123168.
- Firetto Carlino, M., L. Scarfi, F. Cannavò, G. Barberi et al. (2022). Frequency-magnitude distribution of earthquakes at Etna volcano unravels critical stress changes along magma pathways, *Commun. Earth Environ.*, 3, 68, doi:10.1038/s43247-022-00398-6.
- Fischer, T. P. and A. Aiuppa (2020). AGU Centennial Grand Challenge: Volcanoes and deep carbon global CO₂ emissions from subaerial volcanism – Recent progress and future challenges, *Geochem. Geophys. Geosyst.*, 21, e2019GC008690, doi:10.1029/2019GC008690.
- Giacomoni, P. P., C. Ferlito, M. Coltorti, C. Bonadiman et al. (2014). Plagioclase as archive of magma ascent dynamics on “open conduit” volcanoes: the 2001-2006 eruptive period at Mount Etna, *Earth Sci. Rev.*, 138, 371-393, doi:10.1016/j.earscirev.2014.06.009.
- Giammanco, S., B. Krajnc, J. Kotnik and N. Ogrinc (2017). Temporal analysis of $\delta^{13}\text{C}$ CO₂ and CO₂ efflux in soil gas emissions at Mt. Etna: A new tool for volcano monitoring, *Ann. Geophys.*, 60, 6, doi:10.4401/ag-7305.
- Giammanco, S., S. Inguaggiato and M. Valenza (1998). Soil and fumarole gases of Mount Etna: geochemistry and relations with volcanic activity, *J. Volcanol. Geotherm. Res.*, 81, 297-310, doi:10.1016/S0377-0273(98)00012-2.
- Giampiccolo, E., O. Cocina, P. De Gori and C. Chiarabba (2020). Dyke intrusion and stress-induced collapse of volcano flanks: The example of the 2018 event at Mt. Etna (Sicily, Italy), *Sci. Rep.*, 10, 6373, doi:10.1038/s41598-020-63371-3.

- Giuffrida, M., M. Cardone, F. Zuccarello and M. Viccaro (2023). Etna 2011-2022: discoveries from a decade of activity at the volcano, *Earth Sci. Rev.*, 245, 104563, doi:10.1016/j.earscirev.2023.104563.
- Harris, D. M. and W. I. Rose (1996). Dynamics of carbon dioxide emissions, crystallization, and magma ascent: hypotheses, theory, and applications to volcano monitoring at Mount St. Helens, *B. Volcan.*, 58, 163-174, doi:10.1007/s004450050133.
- Hernández, P. A., K. Notsu, J. M. Salazar, T. Mori et al. (2001). Carbon dioxide degassing by advective flow from Usu volcano, Japan, *Science*, 292, 5514, 83-86, doi:10.1126/science.1058450.
- Hilley, G. E., J. L. Lewicki and C. W. Baden (2022). Seasonal and multi-year changes in CO₂ degassing at Mammoth Mountain explained by solid-earth-driven fault valving, *Geophys. Res. Lett.*, 49, e2021GL096595, doi:10.1029/2021GL096595.
- Ilyinskaya, E., S. Mobbs, R. Burton, M. Burton et al. (2018). Globally significant CO₂ emissions from Katla, a subglacial volcano in Iceland, *Geophys. Res. Lett.*, 45, 10332-10341, doi:10.1029/2018GL079096.
- Inguaggiato, S., F. Vita, M. Cangemi, A. Mazot et al. (2017). Stromboli volcanic activity variations inferred by fluids geochemistry observations: Sixteen years of continuous soil CO₂ fluxes monitoring (2000-2015), *Chem. Geol.*, 469, 69-84, doi:10.1016/j.chemgeo.2017.01.030.
- Inguaggiato, S., F. Vita, M. Cangemi, C. Inguaggiato et al. (2021). The monitoring of CO₂ soil degassing as indicator of increasing volcanic activity: The paroxysmal activity at Stromboli volcano in 2019-2021, *Geosciences*, 11, 4, 169, doi:10.3390/geosciences11040169.
- Inguaggiato, S., F. Vita, I. S. Diliberto, C. Inguaggiato et al. (2022). The volcanic activity changes occurred in the 2021-2022 at Vulcano island (Italy), inferred by the abrupt variations of soil CO₂ output, *Sci. Rep.*, 12, 21166, doi:10.1038/s41598-022-25435-4.
- Jácome Paz, M. P., Y. Taran, S. Inguaggiato and N. Collard (2016). CO₂ flux and chemistry of El Chichón crater lake (México) in the period 2013-2015: Evidence for the enhanced volcano activity, *Geophys. Res. Lett.*, 43, 127-134, doi:10.1002/2015GL066354.
- Jácome Paz, M. P., R. Campion, S. Valade, M. A. Armienta Hernández et al. (2026). From quiescence to unrest? Increase in diffuse gas emissions from El Chichón volcano lake (2021-2025), *J. South Am. Earth Sci.*, 180, 106102, doi:10.1016/j.jsames.2026.106102.
- Kahl, M., S. Chakraborty, F. Costa, M. Pompilio et al. (2013). Compositionally zoned crystals and real-time degassing data reveal changes in magma transfer dynamics during the 2006 summit eruptive episodes of Mt. Etna, *Bull. Volcanol.*, 75, 692, doi:10.1007/s00445-013-0692-7.
- Lamberti, M. C., N. Nuñez, G. Velasquez Vargas, G. Pedreros Delgado et al. (2025). Soil carbon dioxide diffuse emission during a volcano-tectonic seismic Swarm at Laguna del Maule volcanic field, *J. South Am. Earth Sci.*, 165, 105689, doi:10.1016/j.jsames.2025.105689.
- Lesne, P., B. Scaillet, M. Pichavant and J. M. Bény (2011). The carbon dioxide solubility in alkali basalts: an experimental study, *Contrib. Mineral. Petrol.*, 162, 1, 153-168, doi:10.1007/s00410-010-0585-0.
- Lewicki, J. L. (2021). Long-term year-round observations of magmatic CO₂ emissions on Mammoth Mountain, California, USA, *J. Volcanol. Geother. Res.*, 418, 107347, doi:10.1016/j.jvolgeores.2021.107347.
- MacDonald, A., T. Ubide, S. Mollo and J. Taddeucci (2024). Spatial and temporal mush heterogeneity during eruptions recorded in clinopyroxene from the 2021 paroxysms at Mt. Etna, Italy, *Contrib. Mineral. Petrol.*, 179, 99, doi:10.1007/s00410-024-02174-5.
- Marchese, F., C. Filizzola, T. Lacava, A. Falconieri et al. (2021). Mt. Etna paroxysms of February-April 2021 monitored and quantified through a multi-platform satellite observing system, *Remote Sens.*, 13, 3074, doi:10.3390/rs13163074.
- Marrero Diaz, R., D. López, N. M. Perez, E. Custodio et al. (2015). Carbon dioxide and helium dissolved gases in groundwater at central Tenerife Island, Canary Islands: chemical and isotopic characterization, *Bull. Volcanol.*, 77, 86, doi:10.1007/s00445-015-0969-0.
- Matias, D., M. Antlauf, F. Viveiros, L. Moreno et al. (2024). Monitoring hydrothermal fumaroles in the Azores archipelago-Applications and sources of analytical uncertainties, *J. Volcanol. Geotherm. Res.*, 450, 108076, doi:10.1016/j.jvolgeores.2024.108076.
- Mazot, A., F. M. Schwandner, B. Christenson, C. E. J. de Ronde et al. (2014). CO₂ discharge from the bottom of volcanic Lake Rotomahana, New Zealand, *Geochem. Geophys. Geosyst.*, 15, 577-588, doi:10.1002/2013GC004945.
- Melián, G. V., P. A. Hernández, N. M. Pérez, M. Asensio Ramos et al. (2021). Insights from Fumarole Gas Geochemistry on the Recent Volcanic Unrest of Pico do Fogo, Cape Verde, *Front. Earth Sci.*, 9, 631190, doi:10.3389/feart.2021.631190.

- Mollo, S., P. P. Giacomoni, M. Coltorti, C. Ferlito et al. (2015). Reconstruction of magmatic variables governing recent Etnean eruptions: constraints from mineral chemistry and P-T- fO_2 - H_2O modelling, *Lithos*, 212-215, 311-320, doi:10.1016/j.lithos.2014.11.020.
- Mollo, S., A. Pontesilli, P. Moschini, F. Palummo et al. (2022). Modeling the crystallization conditions of clinopyroxene crystals erupted during February-April 2021 lava fountains at Mt. Etna: implications for the dynamic transfer of magmas, *Lithos*, 420, 106710, doi:10.1016/j.lithos.2022.106710.
- Moretti, R., N. Métrich, I. Arienzo, V. Di Renzo et al. (2017). Degassing vs. eruptive styles at Mt. Etna volcano (Sicily, Italy). Part I: Volatile stocking, gas fluxing, and the shift from low-energy to highly explosive basaltic eruptions, *Chem. Geol.*, 471, 92-100, doi:10.1016/j.chemgeo.2017.09.017.
- Morita, M., T. Mori, A. Yokoo, T. Ohkura et al. (2019). Continuous monitoring of soil CO_2 flux at Aso volcano, Japan: the influence of environmental parameters on diffuse degassing, *Earth Planets Space*, 71, 1, doi:10.1186/s40623-018-0980-8.
- Murru, M., C. Montuori, M. Wyss and E. Privitera (1999). The locations of magma chambers at Mt. Etna, Italy, mapped by b-values, *Geophys. Res. Lett.*, 26, 2553-2556, doi:10.1029/1999GL900568.
- Neri, M., V. Acocella and B. Behncke (2004). The role of the Pernicana Fault System in the spreading of Mt. Etna (Italy) during the 2002-2003 eruption, *Bull. Volcanol.*, 66, 5, 417-430, doi:10.1007/s00445-003-0322-x
- Padrón, E., N. M. Pérez, F. Rodríguez, G. Mellian et al. (2015). Dynamics of diffuse carbon dioxide emissions from Cumbre Vieja volcano, La Palma, Canary Islands, *Bull. Volcanol.*, 77, 28, doi:10.1007/s00445-015-0914-2.
- Palano, M., M. Viccaro, F. Zuccarello and S. Gresta (2017). Magma transport and storage at Mt. Etna (Italy): A review of geodetic and petrological data for the 2002-03, 2004 and 2006 eruptions, *J. Volcanol. Geotherm. Res.*, 347, 149-164, doi:10.1016/j.jvolgeores.2017.09.009.
- Palano, M., G. Pezzo and C. Chiarabba (2024). Magma budget, plutonic growth and lateral spreading at Mt. Etna, *Commun. Earth Environ.*, 5, 95, doi:10.1038/s43247-024-01267-0.
- Paonita, A., M. Liuzzo, G. Salerno, C. Federico et al. (2021). Intense overpressurization at basaltic open-conduit volcanoes as inferred by geochemical signals: The case of the Mt. Etna December 2018 eruption, *Sci. Adv.*, 7, 36, eabg6297, doi:10.1126/sciadv.abg6297.
- Papale, P., R. Moretti and D. Barbato (2006). The compositional dependence of the saturation surface of $H_2O + CO_2$ fluids in silicate melts, *Chem. Geol.*, 229, 1-3, 78-95, doi:10.1016/j.chemgeo.2006.01.013.
- Pérez, N. M., P. A. Hernández, G. Padilla, D. Nolasco et al. (2011). Global CO_2 emission from volcanic lakes, *Geology*, 39, 3, 235-238, doi:10.1130/G31586.1.
- Pérez, N. M., G. Padilla, E. Padrón, P. A. Hernández et al. (2012). Precursory diffuse CO_2 and H_2S emission signatures of the 2011-2012 El Hierro submarine eruption, Canary Islands, *Geophys. Res. Lett.*, 39, L16311, doi:10.1029/2012GL052410.
- Pérez, N. M., G. V. Melián, P. A. Hernández, E. Padrón et al. (2022). Diffuse CO_2 degassing precursors of the January 2020 eruption of Taal volcano, Philippines, *Sci. Rep.*, 12, 19091, doi:10.1038/s41598-022-22066-7.
- Pilet, S., J. Reymond, L. Rochat, R. A. Corsaro et al. (2026). Mount Etna as a leaking pipe of magmas from the low velocity zone, *J. Geophys. Res., Solid Earth*, 131, e2025JB032785, doi:10.1029/2025JB032785.
- Price, R. E. and D. Giovannelli (2017). A review of the geochemistry and microbiology of marine shallow-water hydrothermal vents, In *Ref. Mod. Earth Syst. Environ. Sci.*, Elsevier, Amsterdam, The Netherlands, doi:10.1016/B978-0-12-409548-9.09523-3.
- Romano, R., F. Lentini, C. Sturiale, C. Amore et al. (1979). Carta geologica del Monte Etna, scala 1:50.000, *Litogr. Art. Cartogr.*, Firenze.
- Shimoike, Y., K. Kazahaya and H. Shinohara (2002). Soil gas emission of volcanic CO_2 at Satsuma-Iwojima volcano, Japan, *Earth Planets Space*, 54, 239-247, doi:10.1186/BF03353023.
- Spilliaert, N., P. Allard, N. Métrich and A. V. Sobolev (2006). Melt inclusion record of the conditions of ascent, degassing, and extrusion of volatile-rich alkali basalt during the powerful 2002 flank eruption of Mount Etna (Italy), *J. Geophys. Res., Solid Earth*, 111, B04203, doi:10.1029/2005JB004104.
- Takano, K., N. Aoyanagi, D. Ichihashi and E. Uchino (2024). Inter-annual variations in the chemical and thermal properties of well waters from the volcanic hydrothermal areas: Usu Volcano, Hokkaido, Japan, *Limnology*, 25, 211-218, doi:10.1007/s10201-023-00736-3.
- Viccaro, M., C. Ferlito, L. Cortesogno, R. Cristofolini et al. (2006). Magma mixing during the 2001 event at Mount Etna (Italy): Effects on the eruptive dynamics, *J. Volcanol. Geotherm. Res.*, 149, 139-159, doi:10.1016/j.jvolgeores.2005.06.004.

- Viveiros, F., C. Cardellini, T. Ferreira, S. Caliro et al. (2010). Soil CO₂ emissions at Furnas volcano, São Miguel Island, Azores archipelago: Volcano monitoring perspectives, geomorphologic studies, and land use planning application, *J. Geophys. Res.*, 115, B12208, doi:10.1029/2010JB007555.
- Viveiros, F., M. Marcos, C. Faria, J. L. Gaspar et al. (2017). Soil CO₂ Degassing Path along Volcano-Tectonic Structures in the Pico-Faial-São Jorge Islands (Azores Archipelago, Portugal), *Front. Earth Sci.*, 5, 50, doi:10.3389/feart.2017.00050
- Werner, C., D. Bergfeld, C. D. Farrar, M. P. Doukas et al. (2014). Decadal-scale variability of diffuse CO₂ emissions and seismicity revealed from long-term monitoring (1995-2013) at Mammoth Mountain, California, USA, *J. Volcanol. Geotherm. Res.*, 289, 51-63, doi:10.1016/j.jvolgeores.2014.10.020.
- Werner, C., T. P. Fischer, A. Aiuppa, M. Edmonds et al. (2019). Carbon dioxide emissions from subaerial volcanic regions: Two decades in review, In *Deep Carbon: Past to Present*, B. N. Orcutt, I. Daniel, R. Dasgupta (Eds.), Cambridge University Press, Cambridge, UK, 88-236.
- Woitischek, J., N. Mingotti, M. Edmonds and A. W. Woods (2021). On the use of plume models to estimate the flux in volcanic gas plumes, *Nat. Commun.*, 12, 2719, doi:10.1038/s41467-021-22159-3.
- Zhang, S., Y. Hua, D. Zhao, Y. Xu et al. (2026). Seismic constraints on the 3-D magma conduit system of Mount Etna, *Geochem., Geophys., Geosyst.*, 27, e2025GC012831, doi:10.1029/2025GC012831.

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