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Near Real-Time Petrologic Monitoring on Volcanic Glass to Infer Magmatic Processes During the February–April 2021 Paroxysms of the South-East Crater, Etna

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The South-East crater of Etna (SEC) is the most active summit crater over the last 20 years, producing lava fountains in 2000, 2007–08, and 2011–14. It has been monitored by the INGV Etna Observatory by instrumental networks, field surveys and petrologic monitoring. The syn-eruptive petrologic monitoring consists of an articulated work chain which is generally carried out within 24 h from the moment the sample was emplaced to detect possible changes of magma composition episode by episode, as well as over a longer period. The findings of petrologic monitoring are integrated with the results provided by geophysical networks and gas geochemistry to check the volcano's behavior during the eruption and to communicate potentially dangerous variations in eruptive features to the local authorities. This paper presents the variation of volcanic glass compositions during the paroxysmal activity of the SEC, which began in December 2020 and climaxed with 17 episodes from 16 February to 1 April 2021. We infer pre-eruptive magmatic processes (e.g., fractional crystallization and mixing) based on temporal trends of some key compositional parameters (i.e., CaO/Al_2O_3; FeO_{tot}/MgO). Correlation between magma dynamics and volcanological characteristics of the paroxysms requires future studies. We demonstrated that petrologic monitoring carried out during a volcanic crisis at Etna, as well as in other volcanoes worldwide, may be crucial to acquire preliminary insights into the structure of the plumbing system and the pre-eruptive processes governing the eruptive activity. Interestingly, this goal has been achieved also thanks to the collaboration with local citizens, who kindly contributed to collecting samples.

Keywords: Etna summit eruptions, lava fountains, petrologic monitoring, glass compositions, mixing, fractional crystallization

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INTRODUCTION

Etna, one of the most active volcanoes in the world, produces various types of eruptions, including both flank and summit eruptions from the four summit craters of the volcano, named Voragine (VOR), Bocca Nuova (BN), North-East (NEC) and South-East (SEC) (**Figure 1**). The SEC has been the most active crater of the last 20 years, generating periods of effusive activity interspersed with

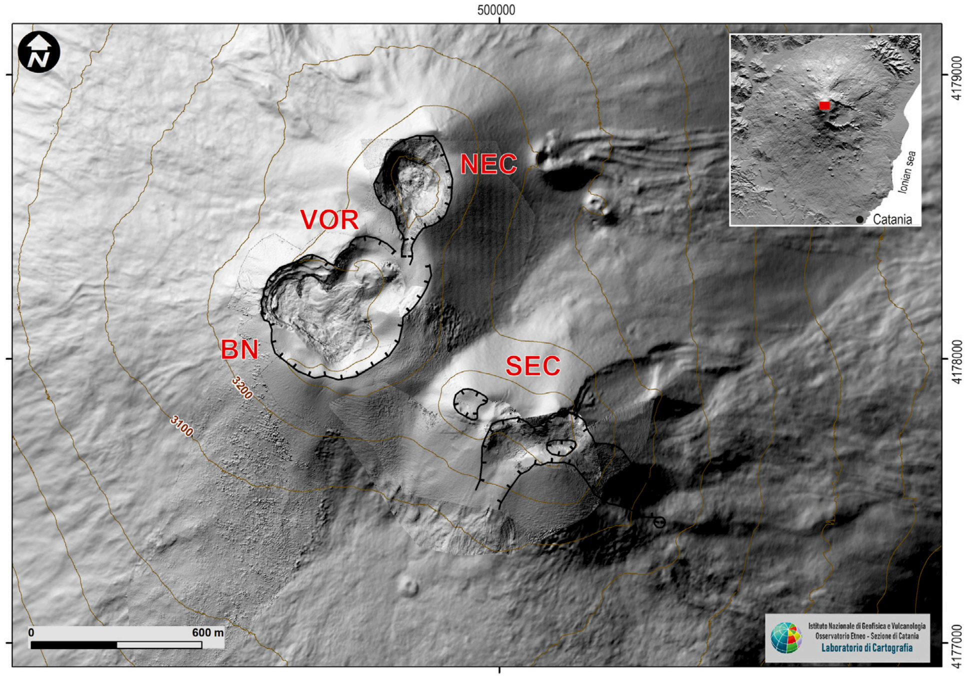

FIGURE 1 | Digital elevation model (DEM) of the summit area of Etna modified from the INGV-OE, Bollettino Settimanale sul monitoraggio vulcanico, geochimico e sismico del vulcano Etna, of 06/04/2021. SEC, South-East Crater; VOR, Voragine; BN, Bocca Nuova; NEC, North-East Crater; barbed line indicates the crater rim. The inset in the upper right corner shows the DEM of Etna volcano, where the summit area is indicated with the red box.

explosive activity of Strombolian type up to lava fountains. In particular, this crater has produced sequences of lava fountain episodes, i.e., the episodic eruptions (Parfitt and Wilson, 1994; Spina et al., 2019) in 2000 (64 episodes, Alparone et al., 2003; Andronico and Corsaro, 2011), 2007-08 (7 episodes, Aiuppa et al., 2010, Andronico et al., 2008, Patanè et al., 2008; Corsaro and Miraglia 2014) and 2011-14 (>50 episodes, Behncke et al., 2014 and references therein). Each episode is characterized by different phases (Alparone et al., 2003) that entail the progressive intensification of Strombolian activity to lava fountains, the formation of a volcanic ash cloud, which can reach tropospheric heights and disperse the fine material even at great distances, and finally the effusion of small lava flows.

In 2021, a new sequence of 17 episodes from the SEC started on 16 February and concluded on 1 April. At the time of writing, a new sequence, which begun on 19 May and continued up to 23 October 2021, has produced 35 new episodes.

The 2021 eruptive activity has been monitored by the Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Etneo (INGV-OE) that provides scientific support to the operational decisions of the National Civil Protection Department (DPC), and deals with the interpretation of the monitoring data from the instrumental networks, field surveys and laboratory analyses. The petrological monitoring, together with gas geochemistry, is the only activity that provides direct information of the magma's properties; the findings of petrologic monitoring are integrated with the results provided by geophysical networks and gas geochemistry to check the volcano's behavior during the eruption and to communicate potentially dangerous variations in eruptive features to the local authorities.

The syn-eruptive petrologic monitoring is essentially aimed at analysing, as quickly as possible, all the useful parameters to detect possible changes of magma composition during an ongoing eruption. To achieve this, we measure the composition of the major elements in the volcanic glass, assuming that it is representative of the pre-eruptive magma composition. This method was successfully applied to study the 2004–05 Etna flank eruption, when samples of effusive activity were quenched with water to inhibit crystallization (Corsaro and Miraglia, 2005); it was also used to investigate the increase of explosive activity from February 2004 at Stromboli (Corsaro et al., 2005), by distinguishing Low Porphyritic (LP) and High Porphyritic (HP) magma (Francalanci et al., 1999; Métrich et al., 2010; Di Stefano et al., 2020; Viccaro et al., 2021).

In this paper, we show the efficiency of petrological monitoring, as described above, to study the paroxysms (i.e., lava fountains) of the SEC, which started in December 2020 and climaxed with 17 episodes from 16 February to 1 April 2021. The temporal trends of the compositional parameters are very detailed because all the paroxysms have been sampled. This sampling strategy allowed us to check the volcano's behaviour episode by episode, in order to communicate possible variations in eruptive features to the DPC during the eruption. Secondly, the increasingly extended compositional dataset as the eruption proceeded, enabled evaluating changes in the magma composition over a longer period, and to hypothesize the pre-eruptive magmatic processes

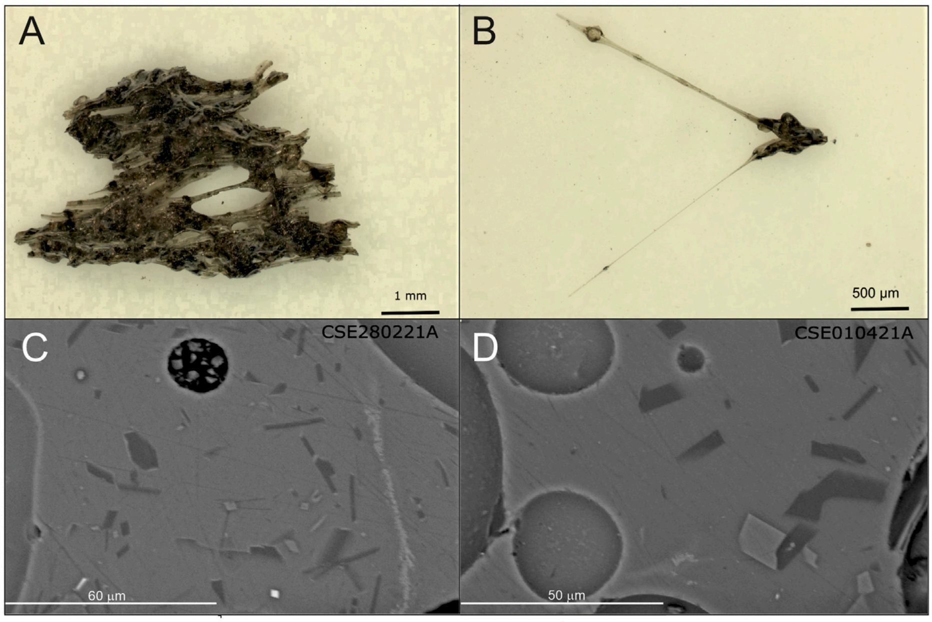

FIGURE 2 | Multi focal plane image in polarized reflected light acquired with stereomicroscope of **(A)** a lapillo and of **(B)** a clast of ash. BSE image acquired with SEM of groundmass glass **(C,D)** containing less than 15% microlites.

TABLE 1 | Selected average (±σ) glass compositions of the SEC products erupted from 16 February to 4 March 2021.

Sample	CSE160221E	CSE180221A	CSE190221H	CSE20221D	CSE220221A	CSE240221A	CSE280221A	CSE020321A	CSE040321C
Date	16 February 2021	18 February 2021	19 February 2021	20 February 2021	22 February 2021	24 February 2021	28 February 2021	2 March 2021	4 March 2021
Type	Lapilli	Lapilli	Lapilli	Ash	Lapilli	Ash	Lapilli	Ash	Ash
SiO_2	47.51 (0.24)	49.01 (0.21)	47.81 (0.14)	47.03 (0.35)	47.13 (0.18)	47.48 (0.19)	46.65 (0.29)	49.01 (0.30)	48.67 (0.28)
TiO_2	2.06 (0.08)	2.10 (0.08)	2.12 (0.08)	2.19 (0.14)	2.07 (0.04)	2.06 (0.08)	2.14 (0.05)	2.23 (0.06)	2.17 (0.05)
Al_2O_3	16.11 (0.16)	16.61 (0.08)	15.89 (0.13)	15.56 (0.08)	15.81 (0.10)	15.91 (0.08)	15.66 (0.28)	16.18 (0.28)	16.09 (0.17)
FeO_{tot}	10.91 (0.21)	11.13 (0.18)	11.22 (0.24)	11.51 (0.09)	11.28 (0.19)	11.20 (0.17)	11.60 (0.23)	11.17 (0.26)	10.81 (0.21)
MnO	0.22 (0.05)	0.25 (0.05)	0.22 (0.05)	0.27 (0.07)	0.21 (0.07)	0.22 (0.06)	0.22 (0.02)	0.22 (0.04)	0.21 (0.05)
MgO	3.95 (0.09)	4.12 (0.09)	3.98 (0.09)	3.82 (0.04)	4.05 (0.09)	4.08 (0.06)	4.33 (0.07)	3.81 (0.11)	3.70 (0.08)
CaO	8.95 (0.11)	9.06 (0.07)	8.93 (0.08)	8.94 (0.03)	9.08 (0.08)	9.03 (0.09)	9.33 (0.18)	8.88 (0.10)	8.59 (0.12)
Na_2O	4.10 (0.13)	4.05 (0.14)	4.04 (0.08)	3.84 (0.06)	3.81 (0.15)	4.10 (0.09)	3.87 (0.30)	4.12 (0.17)	4.43 (0.12)
K_2O	2.91 (0.07)	2.95 (0.04)	2.92 (0.05)	3.00 (0.03)	2.84 (0.06)	2.82 (0.08)	2.78 (0.07)	3.02 (0.09)	3.05 (0.08)
P_2O_5	0.33 (0.05)	0.41 (0.03)	0.37 (0.04)	0.39 (0.03)	0.35 (0.04)	0.36 (0.03)	0.36 (0.05)	0.44 (0.06)	0.43 (0.04)
Cl	0.13 (0.05)	0.18 (0.03)	0.20 (0.02)	0.16 (0.03)	0.17 (0.04)	0.17 (0.02)	0.19 (0.03)	0.17 (0.02)	0.20 (0.03)
Total	97.17	99.86	97.69	96.69	96.81	97.43	97.12	99.26	98.34
CaO/Al_2O_3	0.56 (0.003)	0.55 (0.001)	0.56 (0.002)	0.57 (0.001)	0.57 (0.002)	0.57 (0.002)	0.60 (0.005)	0.55 (0.005)	0.53 (0.002)
FeO_{tot}/MgO	2.76 (0.022)	2.70 (0.029)	2.82 (0.020)	3.02 (0.022)	2.79 (0.026)	2.74 (0.019)	2.68 (0.037)	2.93 (0.047)	2.92 (0.023)

(e.g., fractional crystallization and mixing) responsible for the observed compositional variations.

THE ERUPTIVE ACTIVITY OF THE SOUTH-EAST CRATER FROM 2020 TO APRIL 2021

The volcanic activity of the SEC examined in this work covers the interval January 2020- April 2021, in order to acquire a full picture of the phenomena, which preceded the study period (INGV-OE, Bollettini Settimanali sul monitoraggio vulcanico, geochimico e sismico del vulcano Etna, from 07/01/2020 to 06/04/2021 at: https://www.ct.ingv.it/index.php/monitoraggio-e-sorveglianza/prodotti-del-monitoraggio/bollettini-settimanali-multidisciplinari).

During the first quarter of 2020, the SEC produced small and rare ash emissions. The volcanic activity resumed in April with occasional and low intensity Strombolian explosions, which occasionally culminated in more vigorous explosive activity, as

TABLE 2 | Selected average (±σ) glass compositions of the SEC products erupted from 4 March to 1 April 2021.

Sample	CSE040321E	CSE070321D	CSE100321A	CSE120321A	CSE150321A	CSE170321B	CSE190321B	CSE240321A	CSE010421A
Date	4 March 2021	7 March 2021	10 March 2021	12 March 2021	15 March 2021	17 March 2021	19 March 2021	24 March 2021	1 April 2021
Type	lapilli	lapilli	lapilli	lapilli	lapilli	ash	lapilli	ash	lapilli
SiO_2	48.60 (0.23)	49.47 (0.14)	47.87 (0.24)	48.34 (0.22)	49.73 (0.23)	47.65 (0.29)	48.58 (0.26)	48.49 (0.30)	49.36 (0.21)
TiO_2	2.10 (0.07)	2.11 (0.07)	2.19 (0.08)	2.16 (0.04)	2.09 (0.05)	2.20 (0.10)	2.20 (0.07)	2.17 (0.11)	2.12 (0.10)
Al_2O_3	16.21 (0.15)	16.50 (0.22)	15.70 (0.19)	15.61 (0.17)	16.47 (0.21)	15.59 (0.15)	16.00 (0.15)	15.65 (0.23)	16.50 (0.14)
FeO_{tot}	10.67 (0.07)	11.01 (0.27)	11.19 (0.28)	11.32 (0.31)	10.88 (0.11)	11.09 (0.18)	11.30 (0.20)	10.73 (0.20)	10.92 (0.20)
MnO	0.23 (0.05)	0.22 (0.06)	0.22 (0.04)	0.21 (0.06)	0.21 (0.04)	0.22 (0.03)	0.23 (0.05)	0.22 (0.03)	0.22 (0.05)
MgO	3.90 (0.09)	4.14 (0.05)	3.69 (0.26)	3.65 (0.18)	3.81 (0.09)	3.48 (0.08)	3.70 (0.12)	3.45 (0.07)	3.66 (0.09)
CaO	8.72 (0.08)	8.91 (0.15)	8.77 (0.12)	8.53 (0.09)	8.61 (0.08)	8.67 (0.13)	8.87 (0.13)	8.44 (0.14)	8.63 (0.13)
Na_2O	4.17 (0.10)	4.58 (0.10)	4.23 (0.08)	4.34 (0.34)	4.54 (0.16)	4.39 (0.16)	4.31 (0.13)	4.17 (0.11)	4.76 (0.11)
K_2O	3.05 (0.07)	2.97 (0.10)	3.03 (0.06)	3.12 (0.06)	3.10 (0.06)	3.11 (0.07)	3.13 (0.10)	3.16 (0.05)	3.15 (0.08)
P_2O_5	0.43 (0.04)	0.42 (0.05)	0.39 (0.04)	0.43 (0.04)	0.44 (0.03)	0.40 (0.03)	0.39 (0.03)	0.41 (0.04)	0.34 (0.05)
Cl	0.19 (0.03)	0.19 (0.02)	0.17 (0.02)	0.18 (0.04)	0.19 (0.02)	0.18 (0.03)	0.18 (0.03)	0.20 (0.03)	0.19 (0.03)
Total	98.27	100.50	97.45	97.88	100.07	96.98	98.90	97.09	99.86
CaO/Al_2O_3	0.54 (0.001)	0.54 (0.002)	0.56 (0.002)	0.55 (0.002)	0.52 (0.002)	0.56 (0.002)	0.55 (0.002)	0.54 (0.003)	0.52 (0.002)
FeO_{tot}/MgO	2.74 (0.025)	2.66 (0.024)	3.04 (0.041)	3.10 (0.030)	2.86 (0.024)	3.19 (0.025)	3.05 (0.030)	3.11 (0.031)	2.98 (0.022)

TABLE 3 | Selected average (±σ) glass compositions of the SEC products erupted during the paroxysms of December 2020 and January 2021.

Sample	CSE131220F	CSE211220	CSE180121
Date	13 December 2020	21 December 2020	18 January 2021
Type	lapilli	ash	ash
SiO_2	48.4 (0.37)	48.5 (0.24)	48.14 (0.29)
TiO_2	2.07 (0.09)	2.05 (0.05)	2.14 (0.09)
Al_2O_3	16.06 (0.15)	16.13 (0.12)	16.27 (0.02)
FeO_{tot}	10.73 (0.24)	11.07 (0.11)	11.26 (0.19)
MnO	0.22 (0.04)	0.25 (0.04)	0.19 (0.07)
MgO	3.78 (0.11)	3.84 (0.10)	3.88 (0.10)
CaO	8.7 (0.10)	8.76 (0.08)	9.06 (0.07)
Na_2O	4.35 (0.11)	4.13 (0.12)	4.1 (0.12)
K_2O	2.95 (0.06)	3.1 (0.08)	2.94 (0.08)
P_2O_5	0.33 (0.06)	0.42 (0.04)	0.35 (0.05)
Cl	0.17 (0.02)	0.18 (0.02)	0.17 (0.03)
Total	97.77	98.43	98.51
CaO/Al_2O_3	0.54 (0.002)	0.54 (0.002)	0.56 (0.003)
FeO_{tot}/MgO	2.84 (0.025)	2.88 (0.033)	2.90 (0.021)

occurred on 19 April. In the following months, discontinuous Strombolian explosions of variable intensity continued, producing ash emission lasting for a few hours, and forming ash plumes up to 5 km high above sea level. Starting from December to the end of January 2021, the explosive activity was interspersed with a few paroxysmal episodes, classified by Andronico et al. (2021) as transitional activity, i.e., "strong Strombolian activity alternating with short periods of lava fountains, causing the formation of an eruption plume associated with moderate ash fallout." They took place on 13, 21 and 22 December 2020 and on 18 January 2021. The paroxysmal activity of the SEC continued in February when, starting from 16 February to 1 April, a sequence of 17 lava fountains took place; more detailed information on this period of activity are in Andronico et al. (2021), Bonaccorso et al. (2021), Calvari et al. (2021), De Gori et al. (2021) and Marchese et al. (2021).

In summary, the volcanic phenomena of the SEC showed increasing intensity throughout 2020, which culminated with the paroxysmal activity of 2021. This pattern was shared, since the end of 2020, with the VOR and BN craters, which produced Strombolian activity of variable intensity and frequent intra-crater lava effusion. We should highlight that, compared with the other craters, SEC activity was the most intense during this period.

MATERIALS AND METHODS

The syn-eruptive petrologic monitoring at INGV-OE consists of an articulated work chain comprising sample collections, archiving, sample preparation, analyses of glass compositions using SEM-EDS and data interpretation. This work should be carried out within 24 h of the sample emplacement; the operative protocol matches the most common procedures adopted by volcano monitoring institutions worldwide (Re et al., 2021).

We sampled small size lapilli (max = 1 cm) and ash (<2 mm) (**Figures 2A,B**), because they preserve air-quenched volcanic glass, and are large enough to be rapidly prepared for analysis with SEM-EDS. All the eruptive episodes have been sampled thanks also to local citizens who kindly helped provide material fallen on their properties. This collaboration has ensured that samples have been collected during the fall or soon after deposition on clean surfaces.

The glass compositions of major elements have been analysed at INGV-OE with an LEO-1430 scanning electron microscope, equipped with an Oxford EDS micro-analytical system (SEM-EDS). Analytical conditions are 20 keV, 1200 nA beam current and XPP matrix correction method (Pouchou and Pichoir, 1986). In order to minimize alkali loss during

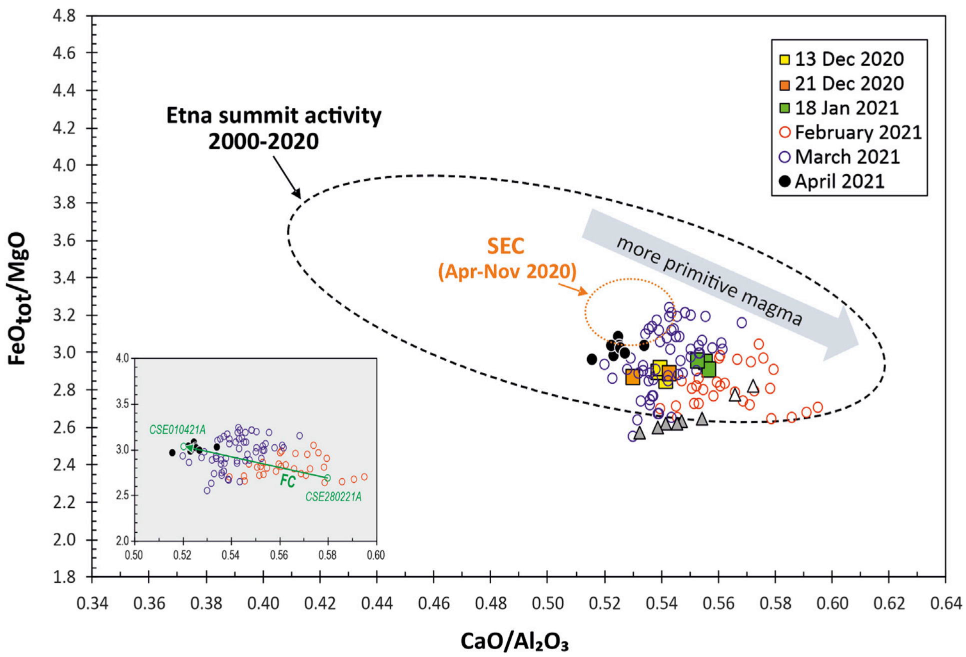

FIGURE 3 | CaO/Al_2O_3 vs. FeO_{tot}/MgO in glass of the SEC products erupted during the paroxysmal activity of December 2020, January 2021 and the sequence of February–April 2021. The glass compositional fields of the SEC in April–November 2020 (orange dotted circle) and of the Etna summit activity in 2000–20 (black dashed line), are also plotted. The compositions of glasses emitted during the SEC paroxysmal activity of 15–17 May 2000 (grey triangle) and 23 November 2013 (open triangles) are also plotted for comparison (Corsaro and Miraglia, 2021). The grey arrow indicates more primitive magma compositions according to Corsaro and Pompilio (2004). In the inset, the fractional crystallization process from the most primitive composition of February (sample CSE280221A) to one of the most evolved of April (sample CSE010421A) is depicted by the green arrow (FC).

analysis, a square raster of 10 microns is used. The accuracy of measurements has been checked through replicate analyses of the international standard VG-2 Glass basaltic, USNM 111240/52 (Jarosewich et al., 1980). The precision, expressed as relative standard deviation, is less than 1% for SiO_2, Al_2O_3, FeO, MgO and CaO and less than 3% for TiO_2, MnO, Na_2O, K_2O and P_2O_5 (Miraglia, 2012). The analyses have been performed in groundmass glass containing less than 15% microlites (**Figures 2C,D**). Each value is the average of 10–15 analyses (**Tables 1–3**, Miraglia, 2021c and Miraglia, 2021d).

RESULTS

The major element compositions of volcanic glass have been measured in lapilli and ash erupted by the SEC during all 17 paroxysms of February–April 2021, of 13, 21 December 2020 and of 18 January 2021 (**Tables 1–3**). Data have been plotted in a CaO/Al_2O_3 vs. FeO_{tot}/MgO diagram (**Figure 3**) where, following Corsaro and Pompilio (2004), the main compositional trend (see grey arrow in **Figure 3**) results from the crystallization of plagioclase, clinopyroxene and olivine) at shallow depth. In other words, plotting analyses of samples on this diagram can be used to qualitatively evaluate if magma composition becomes more or less primitive through time. Other variation diagrams (**Figure 4**) complement the analysis of the compositional variation of the analyzed products.

Taking into account the activity of the SEC preceding the 17 lava fountains of 2021, it is interesting to note that (**Figures 3–5**): 1) the Strombolian activity of Apr–November 2020 produces a rather evolved magma compared to the other studied products; 2) the lava fountain of 13 December 2020 marks the eruption of a more primitive magma than before; 3) the trend toward more primitive composition continues during the 21 December 2020 and 18 January 2021 lava fountains.

Over the following sequence of 17 lava fountains, data reveal that (**Figures 3–5**): 1) the paroxysms of February 2021 (from 16 to 28) are sustained by an even more primitive magma (**Table 1**, CaO/Al_2O_3 = 0.55–0.60, FeO_{tot}/MgO = 2.68–3.02; SiO_2 = 46.65–49.01, Na_2O = 3.81–4.10, K_2O = 2.78–3.00) than 18 January (**Table 3**, CaO/Al_2O_3 = 0.56, FeO_{tot}/MgO = 2.90, SiO_2 = 48.14, Na_2O = 4.1, K_2O = 2.94). In particular, on 28 February, one of the most primitive magma of the SEC in the last 20 years was erupted (**Figure 5**), similar (**Figure 3**) to the paroxysms of 15–17 May 2000 and 23 November 2013 (Miraglia, 2021a; Miraglia, 2021b); 2) magma of the March lava fountains (from 2 to 24) is more evolved (**Tables 1**, **2**, CaO/Al_2O_3 = 0.52–0.56, FeO_{tot}/MgO = 2.74–3.19, SiO_2 = 47.65–49.73, Na_2O = 4.12–4.58, K_2O = 2.97–3.16) than February; 3) the last fountain of 1 April produces one of the most evolved magmas (**Table 2**, CaO/Al_2O_3 = 0.52, FeO_{tot}/MgO = 2.98, SiO_2 = 49.36, Na_2O = 4.76, K_2O =

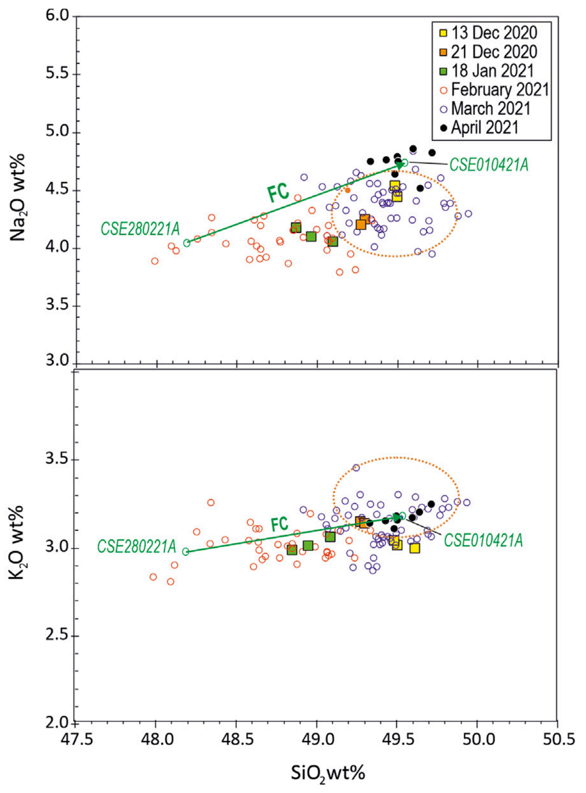

FIGURE 4 | SiO_2 vs. Na_2O and K_2O in glass of the SEC products erupted during the paroxysmal activity of December 2020, January 2021 and the sequence of February–April 2021. The glass compositional field of the SEC in April–November 2020 (orange dotted circle) is also plotted for comparison. The analyses are recalculated to 100 wt%. The description of the fractional crystallization trend (FC) as in **Figure 3**.

3.15) of the sequence, which partly overlaps the compositional field of the April–November 2020 products.

In synthesis, the glass compositions suggest that the paroxysmal activity of the SEC, which started on 13 December 2020, is sustained by an increasing more primitive magma until 28 February, when an inversion occurs. Indeed, magma of the following paroxysms gradually became more evolved, finally going back to the pre-paroxysms compositions of April–November 2020.

DISCUSSION

In order to explain the long-term compositional variability of magma erupted by the SEC described above, we have put forward preliminary hypotheses. Firstly, that the eruption of a more primitive magma, which started in December 2020 and peaked in February 2021, was due to a significant recharge of deeper and more primitive magma in the SEC reservoir, where a 2020 pre-paroxysms magma was stored; the refilling presumably started at the end of 2020 and continued up to the first period (February) of the 2021 paroxysmal activity. Secondly, that the inversion toward more evolved magma composition after February is due to a less efficient transfer of deep magma into the SEC reservoir; this condition enhanced the progressive cooling and crystallization of the stored magma, which gradually evolved and returned to compositions of the 2020 pre-paroxysms period (April–November 2020). We will discuss the first and second point respectively in *Mixing* and *Fractional Crystallization*.

Mixing

The significant recharge of a deeper and more primitive magma in the SEC reservoir, from December 2020 to February 2021 has been modelled assuming that the slightly evolved 2020 pre-paroxysms magma stored in the SEC reservoir until November mixed with a deeper and more primitive magma that progressively intruded it.

The primitive intruding magma has been chosen according to the petrologic studies of the 2001 and 2002–03 flank eruptions of Etna. Indeed, Métrich et al., 2004 and Spilliaert et al. (2006a) found that the primitive melt inclusions hosted in olivine were trapped under total fluid pressure ranging from 400 to 200 MPa. In particular, Spilliaert et al. (2006a) suggested that the primitive basaltic and trachybasaltic magma containing the olivines, ascended from ponding zones located respectively at ≥ 10 km and 6-4 km b.s.l. This background allowed modelling two mixing curves (Langmuir et al., 1978) between the evolved end-member EV (**Figure 6**, i.e., the most evolved glass of the 2020 pre-paroxysms period, erupted by the SEC in November 2020–sample CSE051120-ash, Miraglia, 2021c) and two possible primitive end-members (**Figure 6**): PR1 (i.e., the composition of the 5–41b melt inclusion, hosted in olivine with Fo = 81.5, trapped at 400 MPa, see **Table 2** of Spilliaert et al., 2006a) and PR2 (i.e., the composition of the 5–30b melt inclusion hosted in olivine with Fo = 81.8, trapped at 230 MPa, see **Table 2** of Spilliaert et al., 2006a). Therefore, PR1 and PR2 represent possible magmas stored respectively at ≥ 10 km and 6-4 km b.s.l, which intruded the SEC reservoir and mixed with the EV magma stored there.

Most of our data plot along the two modelled mixing curves (**Figure 6**). In particular, during the paroxysmal activity of 13, 21 December 2020 and 18 January 2021, the erupted magma is the result of a mixing process between EV magma and about 15% of a primitive end-member (poles PM1-PM2). The more primitive magma erupted later, during the paroxysmal activity of February 2021, suggests the involvement of more extended proportions of the PM1-PM2 end-members, up to about 30%.

Therefore, on the basis of our compositional modelling, it may be suggested that, up to November 2020, a EV magma resident in the SEC shallow reservoir had fed the Strombolian activity of the crater (**Figure 7A**). In a period ranging from November to the first half of December 2020, a new magma ascending from a deep zone of the plumbing system (10–5 km b.s.l.) started to intrude the SEC shallow reservoir, where it began to mix with the resident magma. The resulting mixed magma (about 15% of the primitive component in the resident magma) was erupted during the 13, 21 December 2020 and 18 January 2021 paroxysms. Magma transfer from deep zones to the SEC reservoir continued, so that the

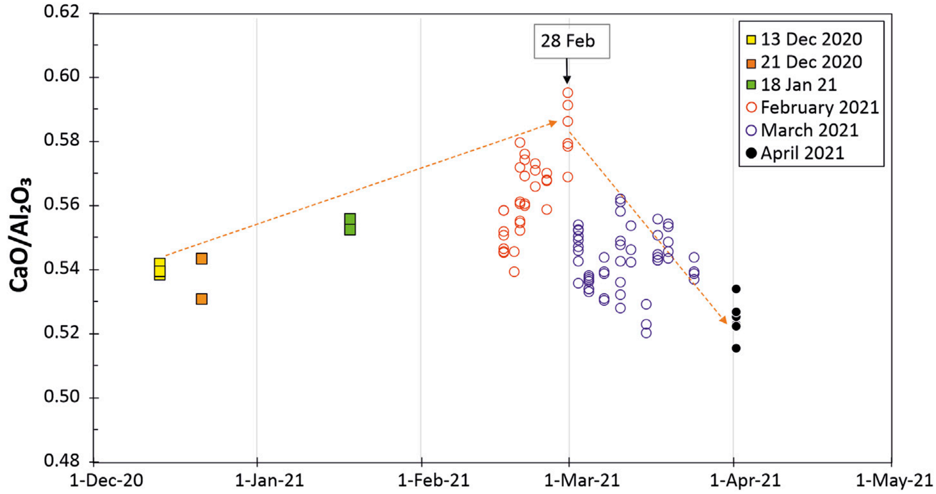

FIGURE 5 | Temporal variation of CaO/Al_2O_3 in glass of the SEC products erupted during the paroxysmal activity of December 2020, January 2021 and the sequence of February-April 2021. The ascending arrow from December 2020 to the end of February 2021 highlights a magma becoming more primitive, suggesting that a gradual intrusion of a new deep magma into the SEC reservoir started from December 2020 and climaxed in February 2021. On the contrary, the descending arrow from March to the last paroxysm of 1 April 2021 indicates an increasing magma evolution owing to fractional crystallization.

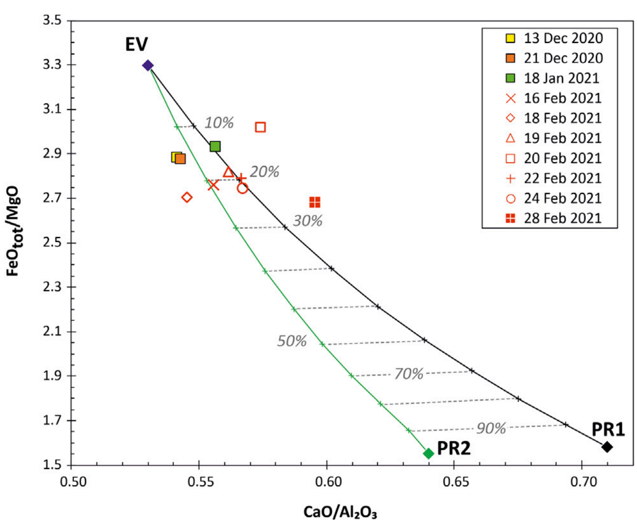

FIGURE 6 | CaO/Al_2O_3 vs. FeO_{tot}/MgO (average values) in glass of the SEC products erupted during the paroxysmal activity from 13 December 2020 to 28 February 2021 (see the dates in the legend). Mixing curves have been modelled between EV, sample CSE051120-ash (Miraglia, 2021c), and respectively: i) PR1 (sample 5–41b of Spilliaert et al., 2006a) and ii) PR2 (sample 5–30b Spilliaert et al., 2006b). Ticks on the mixing lines are the percentage (in grey) of the PR1 or PR2 end-members in the mixed magma. See text for details.

paroxysmal activity of February 2021 was sustained by an even more primitive magma (up to about 30% of the primitive component in the resident magma) (**Figure 7B**).

Mixing between distinct magmas is a well-known process to interpret the compositional variability of the products erupted during the paroxysmal activity of the SEC in 2000 (Andronico and Corsaro, 2011) and 2007–08 (Corsaro and Miraglia, 2014). Indeed, the temporal variation of bulk rock compositions can be explained by a mixing between an evolved magma stored in the SEC reservoir and a new more primitive magma, which intrudes it. Petrologic data (Spilliaert et al., 2006b) set the top of the SEC reservoir at about 1.5 km below the crater, i.e., at the base of the volcanic pile. This position is confirmed by a recent seismic tomography study of Etna (De Gori et al., 2021), which showed two small shallow reservoirs at about 1 km b.s.l. that feed the activity of the summit crater, similar to the 2021 paroxysms; also the strain variations constrain the position of the source that fed the 2021 paroxysmal sequence in the range depth 0.5–1 km b.s.l. (Bonaccorso et al., 2021).

As discussed above, the compositional variations of the erupted products have allowed us to infer that a gradual intrusion of a new deep magma into the SEC reservoir started from December 2020 and climaxed in February 2021. Interestingly, this hypothesis is supported by other monitoring data. Indeed, the reappraisal of volcanic activity is associated with an increase of seismic release started in December 2020, when deep (>12 km) and shallow (<3 km) clusters of earthquakes occurred contemporaneously (De Gori et al., 2021); for the authors, seismic signals have been produced by almost contemporaneous melt injections within magmatic reservoirs at deep and shallow depths. More in detail, the tensile source modeling of the strain recorded by the borehole dilatometer (Bonaccorso et al., 2021) has suggested that the shallow seismic swarm of 19 December 2020 has testified to the migration of fresh magma to a shallow level of the plumbing system.

Fractional Crystallization

The turnaround of glass toward more evolved compositions starting from March to April 2021 has been modelled

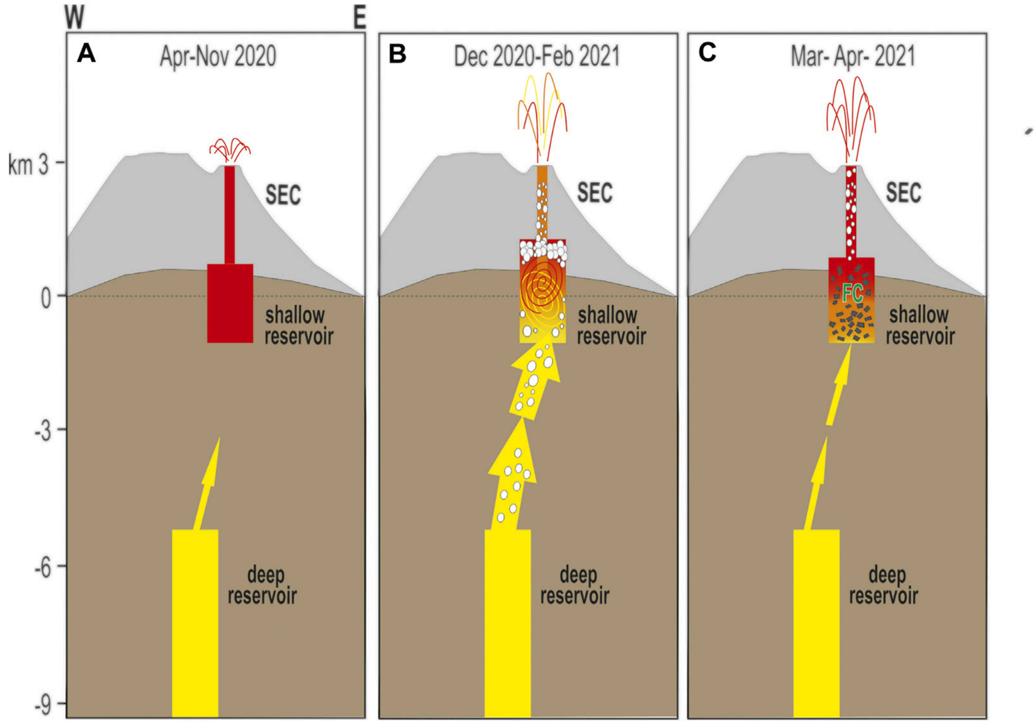

FIGURE 7 | Cartoon illustrating magma dynamics of Etna plumbing system driving the paroxysmal activity of December 2020—April 2021. **(A)** in April-November 2020 the magma stored in the shallow SEC reservoir feeds the explosive activity of the SEC; **(B)** from December 2020 to the end of February 2021 an increasing more primitive magma is erupted, which is the result of a mixing between the magma stored in the SEC reservoir and a new magma ascending from a deep zone of the plumbing system. **(C)** in March-April 2021 the paroxysmal activity is fed by a more evolved magma owing to fractional crystallization (FC). See the text for details.

assuming that the magma stored in the SEC at the end of February evolved owing to fractional crystallization (FC).

To this end, mass balance calculations with XLFRAC (Stormer and Nicholls, 1978) have been performed choosing: the most primitive composition of 28 February glass (sample CSE280221A, average CaO/Al_2O = 0.58 and FeO_{tot}/MgO = 2.70, SiO_2 = 48.19 wt%, Na_2O = 4.06 wt%, K_2O = 2.98 wt%) as parental magma, and one of the most evolved composition of 1 April glass (sample CSE010421A, average CaO/Al_2O_3 = 0.52 and FeO_{tot}/MgO = 3.02, SiO_2 = 49.52 wt%, Na_2O = 4.74 wt%, K_2O = 3.17 wt%) as residual magma (**Figures 3**, **4**). Fractionating minerals are set to include the most common phases that crystallize at shallow conditions since their removal produces a liquid line of descent described by Corsaro and Pompilio (2004), that matches the compositional trend depicted by our samples starting from the end of February. For this model, we use the most primitive compositions of the microphenocrysts present in the parental magma of 28 February 2021, i.e., plagioclase (An = 85), olivine (Fo = 81), clinopyroxene (Wo = 47, En = 39, Fs = 14), and Ti-magnetite (Usp = 36). The results show that the compositional variability of the products erupted from the end of February to April 2021 is well explained by a fractional crystallization process (**Figures 3**, **4**) that involved the magma stored in SEC reservoir in that period (**Figure 7C**). Indeed, the removal of 12% crystals consisting of 4% plagioclase, 1% olivine, 5% clinopyroxene, and 2% Ti-magnetite, provides a good fit (sum of the residuals = 0.08) between measured and modelled compositions.

CONCLUSIVE REMARKS

The petrological monitoring of the paroxysmal activity, which began in December 2020 and culminated with the sequence of 17 episodes from 16 February to 1 April 2021, has enabled us to track the evolution of magma composition, taking into account all the eruptive episodes for the first time at Etna. This goal has been achieved also thanks to the collaboration developed with local citizens, who kindly contributed to collecting samples.

Volcanic glass compositions become progressively more primitive from December 2020 up to the end of February 2021; the trend is later inverted and magma becomes gradually more evolved up to the end of the sequence on 1 April 2021. These compositional features can be explained by increasing degrees of mixing between the magma residing in the shallow SEC reservoir and a new recharging magma ascending from a deep region of the plumbing system (10–5 km b.s.l.); the mixing produced a progressively more primitive magma erupted up to the end of February. When the efficiency of the deep magma transfers and/or of the mixing process decreased, the effect of cooling and crystallization prevailed and the magma present in the SEC reservoir evolved due to fractional crystallization involving about 12% vol. of minerals.

In this framework, the role played by petrologic monitoring during an eruption is of primary importance to acquire preliminary insights into the structure of the plumbing system and the pre-eruptive processes governing the eruptive activity at Etna and other volcanoes worldwide. A stimulating perspective to address in the future would be to understand how magma dynamics affect the volcanological features and the timing of the periodic lava fountains at Etna.

Finally, petrologic monitoring can give an important contribution to the volcanic hazard assessment of active volcanoes. Indeed, its findings can provide information of possible eruptive styles and magnitude of activity, according to the recommendations of Pallister et al. (2019).

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

RC Conceptualization, Formal Analysis, Writing-Original Draft, Visualization LM Conceptualization, Formal Analysis, Investigation, Visualization

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