Inferences on the magmatic plumbing system at Stromboli volcano (Italy) from trace element geochemistry of matrix glasses and minerals in different types of explosive eruptions

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Abstract
Stromboli (Italy) is a basaltic volcano characterized by persistent, mild strombolian activity, occasionally interrupted by lava effusion and more violent explosive events, named major explosions and paroxysms depending on their intensity and magnitude. The normal activity is fed by a shallow and degassed highly porphyritic (HP) shoshonitic basalt carrying about 50 vol.% crystals settled in a shoshonitic glassy matrix (K2O > 3.8 wt.%). The more energetic explosions erupt a deep, volatile-rich, low-porphyritic (LP) magma with < 10 vol.% crystals in a shoshonitic basaltic glassy matrix (K2O < 2.4 wt.%). Products with intermediate glass composition are also found in the more violent explosive events. In this study, we present a new data set of major and trace element contents in matrix glasses and minerals performed in products from different types of explosive activity that occurred at Stromboli between 1998 and 2020. This large data set is used to put constraints on the evolution and architecture of the intermediate plumbing system, where the transformation from LP to HP occurs. Results indicate that, compared to paroxysms, the glassy matrices of the LP pumices from major explosions are richer in incompatible trace elements (and K2O wt.%) due to < 15 wt.% fractionation of clinopyroxene and olivine. This points to a chemical zoning of the deep reservoir and suggests that major explosions are fed by magmas residing in its upper part. Among the major explosions, the homogeneous intermediate glasses in the products from the 19 July 2020 event originate from the interplay of mixing and crystal fractionation processes. The crystallization of euhedral microphenocrysts of An-rich plagioclase suggests that batches of magma can pond and crystallize for few days (< 11) at the base of the intermediate zone of the plumbing system, at pressure coinciding with the entering of plagioclase into the system (< 100 MPa). As a relevant point for understanding the pre- and syn-eruptive magma dynamics, data indicate a positive correlation between the magnitude of the explosions and the depth of the supply magma.

Keywords Stromboli explosive activity · Matrix glass · Trace elements · Petrogenetic processes

Introduction
Stromboli island (Aeolian Archipelago, South Italy) is a steady-state volcano characterized by persistent activity since the eighth century CE (Rosi et al. 2013). The eruptive activity takes place from several vents located within a flat crater area at about 750 m a.s.l. in the upper part of the Sciara del Fuoco, a horseshoe-shaped scar in the NW flank of the island generated by several flank collapses (Tibaldi et al. 2001). The “normal” activity of the volcano consists of continuous degassing accompanied by rhythmic, mild to moderate explosions from a single vent, lasting from a few to tens of seconds, which throw ash, lapilli, and bombs up to heights of several hundreds of meters (Harris and Ripepe 2007; Rosi et al. 2013). This is occasionally interrupted by lava effusion
episodes and more violent explosive events during which several vents can be involved and ejection velocity and volume of products are much higher than during normal explosions. The more violent explosive events (named paroxysms by Mercalli et al. 1907) are short-lived explosions (from tens of seconds to a few minutes) classified as “major explosions” or “paroxysms,” depending on the areal distribution of the products and hazard implications, intensity and magnitude of the eruption, the paroxysms being the most energetic events (Barberi et al. 1993; Harris and Ripepe 2007; Bertagnini et al. 2008; Rosi et al. 2013). Some authors (i.e., Métrich et al. 2021) further distinguished the paroxysms between “small-scale paroxysms” (e.g., 5 April 2003; 15 March 2007; 3 July 2019; 28 August 2019) and “large-scale paroxysms” (e.g., 1930 and 1456 CE eruptions). Each explosion of the normal activity is characterized by a tephra volume of 1–10 m³ and a Mass Discharge Rate of 10⁻²–10⁻³ kg/s; major explosions typically erupt 10⁻²–10⁻³ m³ of tephra with a Mass Discharge Rate of 10⁻¹–10⁻⁰ kg/s, while, during paroxysms, the volume of the erupted products reaches 10⁻¹–10⁻⁰ m³ with Mass Discharge Rate of 10⁻¹–10⁻⁰ kg/s (Rosi et al. 2013 and references therein; Andronico et al. 2021).

Extensive literature, focused on the characterization of geochemical and petrological features of the magmas emitted at Stromboli, reveals that the normal activity is fed by a crystal-rich basaltic-shoshonitic magma, with a shoshonitic matrix glass (K₂O ≥ 3.8 wt.%), hosting about 50 vol.% of crystals (HP magma = Highly Porphyritic), including oscillatory-zoned plagioclase (An₆₂–₉₀), clinopyroxene (Mg# 0.70–0.90; Fs₅–₇) and fairly homogeneous olivine (Fo₇₀–₇₄).

Rims of plagioclase and pyroxene in textural equilibrium with the HP matrix glasses have composition ~ An₆₂–₇₀ (peak at An₆₃) and Mg# 0.73–0.78 (Fs₁₂–₁₄), respectively. Minerals are commonly euhedral, although in a few cases they display rounded rims with compositions out of equilibrium with the groundmass glasses (Landi et al. 2004, 2009; Francalanci et al. 2004; Bertagnini et al. 2008). This magma resides in a degassed shallow reservoir (<3 km), located within the volcanic edifice. The shallow magma body maintains its nearly stationary conditions through a continuous supply of a volatile-rich, low-porphyritic (LP) magma ascending from the deeper portions of the plumbing system, down at 6–9 km. LP magma has a basaltic-shoshonitic matrix glass (K₂O ≤ 1.7–2.4 wt.%), and <10 vol.% of clinopyroxene (Mg# 0.8₄–₀.₉₀; Fs₅–₈) and olivine Fo₈₂–₉₁ (Métrich et al. 2001, 2010, 2021; Francalanci et al. 2004; Landi et al. 2004, 2009; Armienti et al. 2007; Bertagnini et al. 2008).

In detail, olivine compositions Fo₈₂–₉₁ as reverse zoned or composite crystals are peculiar in the products from the large-scale paroxysms and are indicative of a deep recharge (depth > 9 km) accompanying these powerful explosions (Bertagnini et al. 2003, 2008; Métrich et al. 2021). Plagioclase in LP products are only found as reaction/growth rims on phenocrysts mostly inherited from the HP magma, or aggregates of skeletal microlites, with variable composition around An₇₀–An₈₈ (Landi et al. 2004; Andronico et al. 2021). At shallow levels, the LP magma degasses, crystallizes, and mixes with the resident magma, generating the HP magma (Métrich et al. 2001; Landi et al. 2004).

The products with intermediate composition between LP and HP melts show a strongly inhomogeneous glassy matrix that covers the entire range between the two end-members (Andronico et al. 2008; Andronico and Pistolesi 2010; La Felice and Landi 2011a; Pioli et al. 2014). Mineral compositions in equilibrium with these intermediate glasses are until now not documented as phenocrysts, and they can be only found as reaction/growth rims that commonly develop on crystals inherited from the LP or HP magmas (Landi et al. 2008; La Felice and Landi 2011a), making difficult the identification of a distinctive mineral paragenesis.

Magasms with intermediate characteristics are thought to originate from hybridization and mineral dissolution/crystallization during HP/LP magma mixing and degassing, likely within a strongly dynamic, intermediate zone of the feeding system between 1 and 4 km (Francalanci et al. 2004, 2012; Métrich et al. 2010; Landi et al. 2008; La Felice and Landi 2011a; Pioli et al. 2014). However, a physical and chemical model of this zone is up to date not available.

Although during normal activity a small amount of deep-derived LP magma (<3 vol.%) detected in the ash fraction can reach the surface (Schiavi et al. 2010; D’Oriano et al. 2011), paroxysms and most of the major explosions involve relevant volumes of LP magma that mingles with the shallow HP magma during its ascent. The extent of mingling is largely variable among the clasts of a single explosion and among clasts from different paroxysms/major explosions (Bertagnini et al. 2008; Rosi et al. 2013; Andronico et al. 2021; Métrich et al. 2021). In some major explosions, emitted products are characterized by only HP composition (e.g., 8 September 1998; Bertagnini et al. 1999), while other major events are characterized by the emission of both HP and LP magmas, associated with a variable quantity of products with intermediate composition between the two end-members. All the different compositions can be found in a single clast (mingled pumice). Among the previously studied eruptions characterized by the emission of intermediate compositions, the LP end-member is absent only in the products from the 9 January 2005 explosion, a high-energy event ranking between major explosions and normal activity (Andronico et al. 2008; Pioli et al. 2014).

In this work, we present trace element analyses of the glassy matrices and mineral phases of volcanic products that erupted during different types of explosive activity at Stromboli over a period of 22 years. We use this large data set to discuss the role of the different petrogenetic processes (degassing, crystallization, mineral dissolution, magma...
mixing) that occur in the feeding system and lead to the transformation of the LP magma into the HP magma. The aim of the work is to improve the knowledge of the structure and evolution of the volcanic plumbing system with emphasis on the intermediate zone between the deep LP reservoir and the shallow HP magma body. Also, we provide insights into the relationships between the type of explosive activity at Stromboli volcano and the involved sectors of the plumbing system.

**Studied samples**

Studied samples are representative of the whole spectrum of explosive activity that occurred at Stromboli between 1998 and 2020, and correspond to 4 paroxysms, 8 major explosions, and 7 scoriae and/or ash emitted during the normal activity. Samples consist of: (1) mingled pumices sampled in the summit area of the volcano a few days after the more violent explosive events (both major explosions and paroxysms); (2) ash and lapilli emitted during the paroxysms and sampled along the coast or close to the villages of Ginostra and Stromboli; (3) HP scoriae emitted during the whole range of eruption intensity, from paroxysms to major explosions to normal activity; and (4) coarse ash emitted during the normal activity (Table 1; Online Resource 1).

Among the analyzed samples, those emitted before September 2019 were already object of petrographic, mineralogical and compositional studies. In detail, they are: the 5 April 2003 (Métrich et al. 2005), the 15 March 2007 (Métrich et al. 2010), and both the 2019 (Andronico et al. 2021) paroxysms; the 23 August 1998, 8 September 1998, 24 November 1998, 26 August 1999 (Bertagnini et al. 1999 and 2003; Métrich et al. 2001; Landi et al. 2004), and both the November 2009 (La Felice and Landi 2011a) major explosions; and the 18 July 2000 scoriae (ST212; Landi et al. 2004), the ash emitted in October 2011 (EST1; D’Oriano et al. 2011), the 27 July 2019 lapilli and ash (samples 17 and 22c, respectively; Andronico et al. 2021) emitted during normal activity.

Thanks to the effort gained in the frame of the UNO-Project, aimed at the characterization of the ordinary activity to predict the extraordinary, an intensification of the sampling at Stromboli allowed the collection of several samples in the period October 2019–October 2020. They correspond to the normal activity in October 2019 (STRO#1), November 2019 (STRO#8), and October 2020 (ST1020#5), and the products erupted during the major explosion of 19 July 2020. This last can be considered one of the most energetic major explosions that occurred at Stromboli in the past decades (Aiuppa et al., 2021). A survey following this episode allowed us to document that the explosion was characterized by the ejection of large scoria bombs in the summit area

| Sample       | Date          | Type of activity | Material analyzed        | Groundmass       |
|--------------|---------------|------------------|--------------------------|-----------------|
| ST137/ST130  | 23 August 1998| Major explosion  | Mingled pumice           | LP, HP          |
| ST155        | 8 September 1998 | Major explosion  | Scoriae                  | HP              |
| ST168        | 24 November 1998 | Major explosion  | Mingled pumice           | LP, INT, HP     |
| ST178        | 26 August 1999 | Major explosion  | Mingled pumice           | LP, HP          |
| ST212        | 18 July 2000  | Normal activity  | Scoriae                  | HP              |
| ST305        | 5 April 2003  | Paroxysm         | Mingled pumice           | LP, HP          |
| 15/03/07     | 15 March 2007 | Paroxysm         | Mingled pumice           | LP, HP          |
| EST1         | October 2008  | Normal activity  | Coarse ash               | HP              |
| STR081109    | 8 November 2009 | Major explosion  | Mingled pumice           | INT, HP         |
| STRO241109   | 24 November 2009 | Major explosion  | Mingled pumice           | LP, INT, HP     |
| P02          | 3 July 2019   | Paroxysm         | Total sample (coarse ash)| LP, INT, HP     |
| 703a         | 3 July 2019   | Paroxysm         | Mingled pumice           | LP, INT, HP     |
| 15           | 3 July 2019   | Paroxysm         | Scoriae                  | HP              |
| 17           | end of July 2019 | Normal activity  | Lapilli                  | HP              |
| 22c          | end of July 2019 | Normal activity  | Ash                      | HP              |
| 19c          | 28 August 2019 | Paroxysm         | Total sample (coarse ash)| LP, INT, HP     |
| STRO#8       | 20 October 2019 | Normal activity  | Coarse ash               | LP, HP          |
| STRO#1       | 1 November 2019 | Normal activity  | Coarse ash               | HP              |
| STPL801      | 19 July 2020  | Major explosion  | Scoria coated by yellowish glass | INT, HP |
| STPL804      | 19 July 2020  | Major explosion  | Scoria coated by yellowish glass | INT, HP |
| STPL805      | 19 July 2020  | Major explosion  | Single scoria            | HP              |
| ST1020#5     | 10 October 2020 | Normal activity  | Coarse ash               | HP              |
down to 700–750 m in the SW-SE sector, while on the E flank of the edifice the products were concentrated in a rather narrow lobe-shaped area down to 600 m a.s.l. The products deposited on the summit area mainly consist of black HP scoria bombs, partially coated by a highly vesicular, yellowish glass (Fig. 1a, b), while, on the E flank, homogeneous, dense HP scoriae are found. In both deposits, a reddish lithic material, mostly made of altered rocks ripped from the upper conduit and vent area, is abundant both as dm-sized blocks and mm-sized fragments within the scoria bombs. LP pumices were also erupted during this explosion (Bertagnini and Pistolesi personal communication) and likely dispersed from the plume as lapilli in the N–NE sector of the volcano. During our sampling, carried out three months after the major explosion, the LP material erupted during this event was no longer recognizable, due to its intrinsic crumbly character.

For the purpose of the present work, all samples reported in Table 1 were analyzed for their major and trace element glass composition. In addition, the 19 July 2020 samples were investigated for the petrographic and mineralogical features; major and trace element analyses of selected mineral phases were measured in samples ST130 (23 August 1998), ST305 (5 April 2005), and 15 (3 July 2019), and STPL804 (19 July 2020). See Online Resource 1 for details on analyzed samples.

**Methods**

Textural characterization of groundmasses and phenocrysts, and major element composition of mineral phases were investigated at the Istituto Nazionale di Geofisica e Vulcanologia (INGV), Pisa (Italy) by means of a Zeiss EVO MA 10 scanning electron microscope (SEM) working in backscattered electron (BSE) mode, equipped with an Oxford ISIS microanalytical EDS system. The accuracy of EDS analyses is $< 3–4\%$ for most of the major elements and $< 5\%$ for Na$_2$O. Major element compositions of minerals selected for trace element analyses were also obtained by means of a Jeol-JXA8200 microprobe at INGV, Rome (see below).

Trace element composition of few plagioclase (11 spot analyses), pyroxenes (8 spot analyses) and olivines (16 spot analyses) and about 300 spot analyses of microlite-free matrix glasses were performed at the Dipartimento di Fisica e Geologia, University of Perugia (Italy) by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS). The instrumentation consisted of a Teledyne Photon Machine G2 laser ablation device coupled to a Thermo Fisher Scientific iCAP Q quadrupole mass spectrometer (Petrelli et al. 2016a). Circular laser beams ranging from 20 to 40 μm, a repetition rate of 8 Hz, and a laser fluence of $\sim 3.5 \text{Jcm}^{-1}$ have been utilized. Ablation times were about 30 s per spot, preceded by a 25 s background measurement and followed by 25 s of washout. Data reduction was completed with the Iolite 3 software (Paton et al. 2011). The NIST SRM 610 (Pearce et al. 1997) glass and the USGS BCR2G (Wilson 1997) reference materials were used as calibrator and quality control, respectively. The CaO concentrations obtained by electron microprobe were used as internal standard for the glass, plagioclase, and pyroxene, whereas SiO$_2$ was used for the olivine. Under the reported analytical conditions, the precision is better than 11% for concentrations above 0.1 ppm and better than 5% above 20 ppm; the accuracy is always better than 10% with the only exception of Sc, i.e., 12% (Online Resource 1, Petrelli et al. 2016a, b).

In addition, we included in the data set also LA-ICP-MS unpublished analyses of glass (60 spots) and minerals (39 spots), performed at the IGG-CNR of Pavia and the University of Cagliari, in 2001 and 2008, respectively. Precision ($< 6\%$) and accuracy ($< 14\%$) of the LA-ICP-MS analyses performed at Pavia are reported in Online Resource 1; for other details, refer to Landi et al. (2008). For details of LA-ICP-MS analyses performed at Cagliari, refer to D’Oriano et al. (2008).

Major element analyses close to LA spots were performed by means of a Jeol-JXA8200 combined EDS-WDS (five spectrometers with twelve crystals). Data
were collected using 15 kV accelerating voltage and 7.5 nA beam current. The beam diameter was 5 μm with a counting time of 10 and 5 s on peaks and background, respectively. The following internal international standards (MAC LTD) were used: orthoclase (Si, Al, K and Na), apatite (P and Ca), olivine (Mg), pyrite (Fe), rutile (Ti), and rhodonite (Mn). Sodium and potassium were analyzed first to prevent alkali migration effects. The precision and the accuracy of the microprobe were measured through repeated analyses of well-characterized synthetic oxide and mineral secondary standards. Based on counting statistics and analytical uncertainties relative to their reported concentrations, precision for major elements was better than 3% and accuracy better than 2%, except for Na in obsidian 6% (Online Resource 1).

**Results**

The matrix glasses of the products analyzed in the present study show a large textural and compositional variability (SiO₂ 49–53 wt.%; Fig. 1), in agreement with what was observed in the previous works. The HP products have a scoraceous appearance and their groundmasses are characterized by the presence of large bubbles, often irregularly shaped due to the effect of coalescence. In contrast, the LP products are yellow pumiceous material, texturally identified at SEM-BSE for the presence of many and small rounded vesicles, a microlite-free groundmass and the absence of euhedral plagioclase phenocrysts. Despite these textural differences, HP and LP magmas have a very similar whole rock composition (high potassium (HK) to shoshonitic basalts; Fig. 2), which, therefore, it is not suitable for investigating the petrogenetic processes that occur in the intermediate zone of the feeding system, while numerous information can be obtained from the textural and compositional analyses of the matrix glasses. In addition, LP/HP mingling is peculiar to the pumice clasts and whole rock of “pure” unmingled pumice is basically impossible to obtain. Products with intermediate compositions between the two end-members are generally associated with micron-scale spaced mingling textures, always detected straddling the LP and HP portions. Instead, the yellowish material which partially covers a part of the scoria bombs emitted in the 19 July 2020 major explosion (Fig. 2 a, b) is characterized by nearly homogenous glasses with intermediate composition which appear as completely hybridized areas, and the contact between the intermediate and HP portions of the clasts is not shaded (Fig. 2c, d). In these products, the intermediate glasses are characterized by a vesicularity similar to that of LP pumices, even if some vesicles appear collapsed. Few micro-lites of plagioclase with swallowtail edges rapidly grew in the groundmass due to quenching of the less evolved, hotter intermediate magma at the contact with the cooler HP ones. The rheological (i.e., the changes in viscosity due to differences in temperature) differences between the pure HP and “intermediate” glass in the products from 19
July 2020 are also highlighted by the curling margins of the intermediate zones and by the presence of lithic ash clasts (Fig. 2c, d).

**Mineral chemistry of the products from the 19 July 2020 major explosion**

The HP products erupted during the major explosion of 19 July 2020 have the same petrographic characteristics observed in HP products erupted during the normal strombolian activity (Métrich et al. 2001; Francalanci et al. 2004; Landi et al. 2004). The mineral assemblage consists of euhedral crystals of zoned plagioclase, zoned clinopyroxene, and almost homogeneous olivine, hosted in a homogeneous shoshonitic glassy matrix ($K_2O$ 4.0–4.2 wt.%). The rims of phenocrysts in textural equilibrium with the matrix glasses have a nearly homogeneous composition, characterized by plagioclase (pl) $An_{63-68}$, clinopyroxene (cpx) Mg# 0.74–0.77 ($Fs_{13-14}$) and olivine (ol) $Fo_{71-72}$ (Fig. 3a–c) (Table 2). Only a few phenocrysts of olivine with rounded shapes have Mg-rich rims up to $Fo_{74-75}$. Compositions $Fo_{74-75}$ are also found as thin rims (10–20 µm) in the rare olivine microlites (crystals < 100 µm).

The highly vesicular material adhering to the external portion of the HP scoria bombs is characterized by a low crystal content and a rather inhomogeneous mineral chemistry due to the occurrence of crystals with reaction rims inherited from both the HP and LP magmas (Table 2). Mafic minerals (cpx and ol) wetted by the intermediate glass with intermediate composition ($K_2O$ 2.5–3.2 wt.%) are commonly found as crystal aggregates sometimes associated with plagioclase, while plagioclase is mostly present as single crystals. Pyroxenes have rounded and quite homogeneous cores (Mg# 0.69–0.73; $Fs_{15-19}$) mantled by nearly homogeneous rims, with composition from Mg# 0.82 to Mg# 0.86 ($Fs_{8-10}$) (Figs. 3a, 4a, b). The mantles can develop sector zoning (Fig. 4a). Large crystals of pyroxene (~$Fs_{14}$; Mg# 0.75) wetted by the highly vesicular glass ($K_2O$ 2.6–3.2 wt.%), develop thin rims, ~10–15 µm thick, with Mg# 0.80–0.82 ($Fs_{10-11}$). Olivine crystals found in aggregates are characterized by rounded cores ($Fo_{70-73}$) that progressively pass to less evolved rims with $Fo_{76}$ to $Fo_{82}$ (Fig. 3b, 4b). Plagioclase phenocrysts with dissolved labradoritic to bytownitic cores (inherited by HP magma; Landi et al. 2004) and encircled by a sieved texture $An$-rich (~$An_{80-85}$) corona are commonly found (Fig. 4c). It is worthy of noting that the vesicular material is characterized by the occurrence of plagioclase with texture and composition never described in the products of Stromboli. These are microphenocrysts, 200–400 µm large, with $An$-rich ($An_{75-91}$) patchy zoned cores, hosting large vesicles and melt inclusions, that are encircled by undisturbed layers, up to 150 µm large, with homogeneous composition ($An_{67-91}$) (Fig. 4d–f). This type of crystals can be also found in aggregates with pyroxenes Mg# 0.82–0.86 (Fig. 4a). All plagioclase crystals have external rims <10 µm ~ $An_{65-69}$, showing swallowtail final edges.

**Major and trace element content in matrix glasses**

Major and trace element compositions obtained on the whole spectrum of eruption intensity show that minor differences occur among the products related to each eruption in terms of: (1) variation fields of both LP and HP melts; and (2) occurrence and variability of intermediate terms. The $K_2O$ content in the matrix glasses is used to distinguish among the LP ($K_2O < 2.4$ wt.%), the “intermediate” ($K_2O 2.4–3.8$ wt.%) and the HP ($K_2O > 3.8$ wt.%) melts. Although the concentration of some elements (i.e., both major oxides and
Table 2  Average major and trace element composition of matrix glasses, olivine, clinopyroxene and plagioclase representative of LP, intermediate and HP products

| Matrix glass | Average 3 July 2019 (n = 22) | Average 23 August 1998 (n = 10) | Average 19 July 2020 (n = 20) | Average sample 17 (n = 13) | STPL804b-SPOT7 | STPL804A-113 | STPL801 7b spot 86-89 | STPL804A-112 | ST212 (Pl7 rim) |
|--------------|-------------------------------|----------------------------------|-------------------------------|-------------------------------|----------------|----------------|-----------------|----------------|----------------|
| LP (pumice from paroxysm) |                              |                                  |                               |                              |                |                |                 |                 |                |
| LP (pumice from major explosion) |                              |                                  |                               |                              |                |                |                 |                 |                |
| Intermediate (yellow material on scoriae) |                              |                                  |                               |                              |                |                |                 |                 |                |
| HP (scoria) |                              |                                  |                               |                              |                |                |                 |                 |                |
| Major elements (wt.%) | | | | | | | | | |
| SiO₂ | 49.95 (0.67) | 49.16 (0.43) | 51.07 (0.40) | 52.26 (0.37) | 40.15 (0.40) | 39.47 | 52.99 | 52.85 | 51.83 (0.25) | 49.69 (0.31) | 45.20 (0.28) | 51.22 (0.21) |
| TiO₂ | 0.94 (0.07) | 1.12 (0.08) | 1.24 (0.10) | 1.64 (0.10) | 0.20 | 0.36 | 0.45 (0.05) | 1.87 (0.04) |                |                |                |                |
| Al₂O₃ | 17.79 (0.15) | 17.49 (0.21) | 17.43 (0.35) | 15.95 (0.10) | 1.84 | 2.05 | 3.02 (0.05) | 4.93 (0.42) |                |                |                |                |
| FeO | 8.04 (0.19) | 8.34 (0.18) | 8.87 (0.40) | 10.09 (0.13) | 13.57 (0.19) | 16.5 | 3.01 | 4.66 | 5.34 (0.09) | 7.17 (0.18) | 0.58 (0.07) | 0.73 (0.02) |
| MnO | 0.12 (0.03) | 0.15 (0.03) | 0.12 (0.04) | 0.15 (0.03) | 0.18 (0.03) | 0.31 | 0.04 | 0.15 | 0.15 (0.04) | 0.19 (0.01) |                |                |
| MgO | 6.08 (0.12) | 5.98 (0.17) | 4.95 (0.26) | 3.76 (0.08) | 46.12 (0.40) | 43.88 | 17.49 | 17.08 | 16.70 (0.20) | 13.60 (0.44) |                |                |
| CaO | 11.11 (0.19) | 11.07 (0.13) | 9.22 (0.37) | 7.40 (0.12) | 0.25 (0.027) | 0.26 | 23.23 | 22.19 | 21.97 (0.42) | 20.38 (0.53) | 18.51 (0.17) | 13.57 (0.08) |
| Na₂O | 2.53 (0.11) | 2.85 (0.11) | 2.97 (0.23) | 3.28 (0.11) | bdl | bdl | 0.15 | 0.28 | 0.14 (0.03) | 0.63 (0.09) | 1.07 (0.04) | 3.22 (0.07) |
| K₂O | 1.98 (0.09) | 2.13 (0.08) | 2.79 (0.23) | 3.95 (0.08) | bdl | bdl | bdl | bdl |                |                |                |                |
| P₂O₅ | 0.56 (0.09) | 0.70 (0.49) | 0.74 (0.09) | 1.09 (0.07) | bdl | bdl | bdl | bdl |                |                |                |                |
| Total | 99.06 (0.74) | 98.99 (0.49) | 99.50 (0.52) | 99.58 (0.44) | 100.28 (0.63) | 98.95 | 99.62 | 99.60 (0.19) | 100.81 (0.81) |                |                |
| Trace elements (ppm) | | | | | | | | | |
| Li | 9.90 (1.26) | 10.70 (1.13) | 13.03 (1.85) | 16.79 (0.58) | 2.63 (0.16) | 6.8 | 1.1 | bdl | 1.67 (0.67) | 64.8 (0.8) | 5.95 (0.98) |                |
| Sc | 33.79 (0.60) | 33.60 (0.91) | 31.08 (1.76) | 27.46 (0.69) | 13.95 (0.37) | 13.7 | 81 | 100 | 133.20 (16.97) | 417.67 (35.25) | 1.81 (0.35) | 3.79 (0.28) |
| V | 270 (6) | 283 (17) | 302 (19) | 369 (6) | 4.04 (0.16) | 6.26 | 104 | 120 | 259.73 (34.78) | 346.67 (80.96) |                |                |
| Cr | 20.24 (3.22) | 23.95 (4.72) | 9.27 (2.16) | 7.39 (0.67) | 36.45 (4.15) | 12 | 5860 | 3604 | 530.73 (328.55) |                |                |
| Ni | 41.16 (1.68) | 38.33 (3.02) | 25.55 (3.23) | 14.61 (1.06) | 1193 (13) | 677 | 252 | nd | 155.68 (7.52) | 73.40 (2.05) |                |                |
| Ga | 16.49 (0.66) | 16.60 (1.53) | 16.72 (1.37) | 14.61 (1.06) | bdl | bdl | 2.5 | nd | 4.64 (0.69) | 8.65 (0.54) | 16.76 (2.21) |                |
| Rb | 60.94 (2.18) | 64.12 (5.80) | 90.47 (8.72) | 136.07 (3.97) | bdl | bdl | bdl | bdl | 12.73 (3.99) | 1.66 (0.38) |                |                |
| Sr | 676 (11) | 673 (60) | 614 (31) | 535 (10) | 0.02 | bdl | 69 | 58 | 45.23 (1.49) | 125.67 (20.03) | 1189.80 (52.80) | 1360.61 (33.93) |
| Y | 21.50 (0.46) | 25.15 (0.99) | 27.30 (2.33) | 37.26 (1.29) | 0.09 (0.011) | 0.25 | 5.9 | 8 | 16.42 (2.24) | 29.67 (1.33) | 0.21 (0.10) | 0.29 (0.02) |
| Zr | 123 (2.66) | 146 (6) | 175 (18.24) | 267 (8.41) | 0.03 (0.006) | bdl | 9 | 12 | 31.74 (9.63) | 84.37 (10.70) | 0.21 |                |
Table 2 (continued)

|                     | Matrix glass | Olivine | Clinopyroxene | Plagioclase |
|---------------------|--------------|---------|---------------|-------------|
|                     | Average 3 July 2019 (n = 22) | Average 23 August 1998 (n = 10) | Average 19 July 2020 (n = 20) | STPL804A-113 | STPL804A-112 |
| Lp (pumice from paroxysm) | Lp (pumice from major explosion) | Intermediate (yellow material on scoriae) | HP (scoria) | Cpx (Mg#0.91) | Cpx (Mg#0.87) | Cpx (Mg#0.85) | Cpx (Mg#0.75) | ST212 (P17 rim) |
| Nb                  | 13.55 (0.42) | 16.66 (1.61) | 19.77 (2.22) | 31.80 (0.82) | bdl | bdl | 0.09 (0.04) | 3.42 (0.99) | 0.04 |
| Cs                  | 3.78 (0.23)  | 3.92 (0.47)  | 5.70 (0.57)  | 8.75 (0.34)  | bdl | bdl | bdl | bdl | 0.09 |
| Ba                  | 831.52 (16.24) | 896 (42) | 1062 (82.6) | 1416.23 (27.05) | bdl | bdl | 0.05 | bdl | 148.96 (44.31) | 124.02 (18.66) | 590.28 (10.55) |
| La                  | 38.51 (0.83) | 45.44 (1.22) | 52.71 (4.91) | 77.92 (1.54) | bdl | bdl | 2.0 | 2.5 | 15.29 (2.27) | 148.96 (44.31) | 124.02 (18.66) | 590.28 (10.55) |
| Ce                  | 74.69 (1.44) | 87.12 (3.54) | 100.4 (9.64) | 148.60 (3.38) | bdl | bdl | 6.7 | 8.0 | 43.35 (4.49) | 3.19 (0.45) | 9.73 (0.38) |
| Pr                  | 8.41 (0.21) | 10.40 (0.49) | 11.13 (1.09) | 16.40 (0.39) | bdl | bdl | 1.3 | 1.5 | 6.42 (0.55) | 0.31 (0.08) | 0.89 (0.02) |
| Nd                  | 35.02 (0.67) | 42.39 (1.93) | 44.85 (4.45) | 65.63 (2.17) | bdl | bdl | 7 | 8.6 | 31.71 (2.24) | 1.17 (0.25) | 3.01 (0.26) |
| Sm                  | 6.93 (0.35) | 8.18 (0.6) | 9.09 (1.19) | 13.34 (0.38) | bdl | bdl | 1.9 | 2.7 | 8.69 (0.50) | 0.35 (0.11) |
| Eu                  | 1.94 (0.12) | 2.20 (0.10) | 2.32 (0.27) | 2.95 (0.10) | 0.01 | bdl | 0.58 | 0.6 | 2.11 (0.13) | 0.39 (0.09) | 0.88 (0.01) |
| Gd                  | 5.94 (0.46) | 7.11 (0.50) | 7.54 (0.74) | 10.15 (0.33) | bdl | bdl | 2.1 | 2.4 | 7.93 (0.55) | 0.25 | 0.19 (0.11) |
| Tb                  | 0.80 (0.05) | 0.90 (0.05) | 1.01 (0.12) | 1.35 (0.07) | bdl | bdl | 0.24 | 0.3 | 1.09 (0.06) | 0.01 (0.001) |
| Dy                  | 4.40 (0.21) | 5.19 (0.39) | 5.28 (0.62) | 7.37 (0.31) | 0.02 (0.003) | bdl | 1.3 | 1.9 | 3.68 (0.37) | 0.06 (0.01) |
| Ho                  | 0.84 (0.06) | 0.98 (0.06) | 1.03 (0.12) | 1.42 (0.06) | 0.0043 | bdl | 0.25 | 0.34 | 0.71 (0.12) | 1.18 (0.08) |
| Er                  | 2.11 (0.10) | 2.47 (0.24) | 2.66 (0.37) | 3.66 (0.16) | 0.02 (0.006) | bdl | 0.6 | 0.9 | 1.68 (0.29) | 2.67 (0.06) |
| Tm                  | 0.31 (0.04) | 0.34 (0.06) | 0.37 (0.06) | 0.53 (0.04) | bdl | bdl | 0.07 | 0.12 | 0.23 (0.04) | 0.38 (0.03) |
| Yb                  | 1.97 (0.20) | 2.47 (0.41) | 2.46 (0.34) | 3.60 (0.21) | 0.03 (0.006) | bdl | 0.5 | 0.77 | 1.35 (0.27) | 2.41 (0.17) |
| Lu                  | 0.30 (0.03) | 0.34 (0.08) | 0.39 (0.05) | 0.52 (0.03) | 0.01 (0.002) | 0.025 | 0.06 | 0.19 (0.04) | 0.36 (0.03) |
| Hf                  | 2.97 (0.16) | 3.59 (0.35) | 4.28 (0.54) | 6.15 (0.31) | bdl | 0.081 | 0.31 | 0.7 | 1.69 (0.63) | bdl |
| Ta                  | 0.77 (0.05) | 1.00 (0.09) | 1.14 (0.18) | 1.85 (0.07) | bdl | bdl | bdl | 0.02 | bdl |
| Pb                  | 14.84 (0.63) | 17.40 (2.08) | 20.82 (2.01) | 29.34 (0.61) | bdl | bdl | 0.11 | bdl | 0.11 (0.03) | bdl | 1.03 (0.20) | 4.12 (0.22) |
| Th                  | 11.06 (0.36) | 12.88 (0.50) | 17.32 (1.84) | 26.72 (0.81) | bdl | bdl | 0.02 | 0.07 | 2.69 (0.74) |
| U                   | 2.95 (0.10) | 3.32 (0.31) | 4.59 (0.55) | 7.26 (0.31) | bdl | bdl | bdl | bdl | bdl |

n number of analyses; in brackets = standard deviation. Fo = Forsterite mol.%, Mg# = MgO/(MgO + FeO), An = Anorthite mol.%. ol = olivine; cpx = clinopyroxene; pl = plagioclase
trace elements) measured in the intermediate glasses can overlap the field of those of both the LP and HP melts, we decide to maintain this separation, also to be consistent with other studies (Bertagnini et al. 2008 and references therein).

LP glasses

LP pumices (K$_2$O < 2.4 wt.%) analyzed in this work show systematic differences in glass chemistry, both as major and trace element contents (Fig. 5a—d; Table 2). In particular, in the K$_2$O vs CaO binary diagram (Fig. 5a), products from major explosions and paroxysms occupy two distinct fields, partially overlapped, at high K$_2$O and low CaO and low K$_2$O and high CaO, respectively. Pumices erupted during the paroxysms of 2003, 2007, and 2019 cover the same field of variability in terms of major elements. They are characterized, on average, by CaO 10.8–11.9 wt.% and K$_2$O 1.7–2.2 wt.% contents. Major explosions occurred in the period between 1998 and 1999, and on 24 November 2009, there have groundmass composition ranging within CaO 10.4–11.2 wt.% and 2.1 < K$_2$O < 2.4 wt.% (Fig. 5a). Among the other major elements, NaO, SiO$_2$ and FeO increase in melts from paroxysms to major explosions, while MgO and Al$_2$O$_3$ decrease; TiO$_2$ and P$_2$O$_5$ remain quite constant. Although the observed compositional differences are small, they are larger than the analytical errors, and are also highlighted by the trace element contents. Indeed, incompatible trace elements (e.g., Nb, Zr, Ta, Th) show increasing concentration from the matrix glasses of the paroxysms to the major explosions (Fig. 5b, c; Online Resource 1). Ni, V, and Sc compatible with olivine and clinopyroxene have different behavior, where a strong decrease in Ni from paroxysms to major explosions is observed, while Sc and V remain quite unchanged. Another important result concerns the variation of Cr, compatible with the pyroxene structure, that is systematically more abundant in products from 2007 paroxysm.
(Cr = 23.7–29.4 ppm) with respect to the pumices emitted in the 2003 and both 2019 paroxysms (Cr = 12.5–21.8 ppm; Fig. 5d). Pumices from 1998 to 1999 major explosions cover almost the whole range of variation (Cr = 16.3–29.4 ppm) depicted by paroxysms, while products from 24 November 2009 (Cr = 21.9–27.6 ppm) show a decreasing trend of Cr content, starting from the most evolved 2007 products. Two ash fragments from the October 2019 normal activity (STRO#1) have groundmass glasses with textural and compositional features covering the same range of LP pumices erupted during the 24 November 2009 and 28 August 2019, major explosion and paroxysm, respectively.

Intermediate compositions

Groundmass glasses with intermediate composition (2.5 wt.% < K$_2$O < 3.8 wt.%) between LP and HP end-members (INT in Table 1) show different ranges of variation in terms of both major and trace element content (Table 2). These melts are often associated with intra-clasts chemical heterogeneities at the micrometer scale, defining a continuum between the composition of the HP and LP glassy matrices, well documented in both 2019 paroxysms (Andronico et al. 2021) and in some major explosions (e.g., 8 November 2009; Landi and La Felice 2011a). In these cases, the intermediate compositions cover the whole range of CaO/Al$_2$O$_3$ ratios between 0.48 and 0.63. Also, they follow linear trends due to mixing/mingling between the LP and HP end-members.

**Fig. 5** Bivariate diagrams showing the variation of representative major and trace elements in matrix glasses from LP pumices erupted during paroxysms and major explosions. Glasses of pumice from major explosions show higher contents of K$_2$O (a) and incompatible trace elements (b, c) than those of the paroxysms. d The two distinct compositional fields of the 15 March 2007 paroxysm and 5 April 2003 and both 2019 paroxysms are marked by dotted lines. Error bars correspond to 2*RSD%
(Fig. 6a–f). The sample related to the 8 November 2009 major explosion shows an evolved LP glass composition and it is strongly mingled with the HP melts; typical LP end-member (K₂O < 2.4 wt.%) is rare or absent in this sample, as previously reported by La Felice and Landi (2011a). Different trends are detected in groundmasses from the “high-energy explosion” that occurred on 9 January 2005 (Landi et al. 2008) and the major explosion of 19 July 2020 (present work), in which the groundmass glasses have a similar range of variations for major oxides, characterized by a compositional gap with the LP end-member. Despite this similarity, most of the intermediate compositions related to the 19 July 2020 are clustered within a homogeneous field characterized by CaO/Al₂O₃ of 0.51–0.56 wt.%, K₂O of 2.5–3.0 wt.%, and MgO of 4.7–5.3 wt.% (Fig. 6a, b). Incompatible trace elements (Th, Rb) in the products of 19 July 2020 show a slightly negative correlation with CaO/Al₂O₃, in the range of Th = 14.5–19.8 ppm and Rb = 79.5–97 ppm (Fig. 6c, d), while compatible elements are on a horizontal trend (Fig. 6e, f). Samples from 8 November 2009 and 19 July 2020 major explosions show a different correlation of Cr vs CaO/Al₂O₃ (Fig. 6e): in the first case, there is a continuum decrease from the more evolved glass measured in products from 24 November 2009 toward the HP compositional field (Cr = 11.2–21.1 ppm), while the matrix glasses from 19 July 2020 have a quite constant Cr content, around 10 ppm.

Fig. 6 Variation of selected incompatible (K₂O, Th and Rb) and compatible (MgO, Cr and Sc) major and trace elements with respect to CaO/Al₂O₃ ratio, in matrix glasses with chemical composition intermediate between LP and HP end-members, from the products emitted during major explosions and paroxysms. The composition of the LP and HP end-members are reported as fields of variation (LP: yellow; HP: gray). Black dots: 9 January 2005, data from Landi et al. (2008). Error bars correspond to 2*RSD%
HP glasses

Major elements in the HP glasses (K2O 3.9–4.5 wt.%) cover the same compositional range reported in the literature (Table 2) with only small differences among the products erupted during normal, major and paroxysmal activities (Landi et al. 2004, 2011). Incompatible trace elements (e.g., Rb, Zr, La, Ce, Y, Th, Ta) and Sr (compatible in plagioclase) show ranges of variation within 8–12%, close to the analytical error (< 10%). Only Ni (7–15 ppm) and Cr (2–10 ppm) show larger variations (Table 2; Online Resource 1).

Discussion

Inferences on the intermediate zone of the plumbing system from mineral chemistry

Products with intermediate composition erupted during the 19 July 2020 major explosion are characterized by heterogeneous mineral chemistry. The Fe-rich compositions measured at the core of many mafic crystals (e.g., cpx Mg# 0.69–0.73; ol Fo70–73; Fig. 4a, b) can be considered as the remnant of a dissolved crystal belonging to a vertically extended crystal mush developed either during the present activity or in the previous periods (Francalanci et al. 2005, 2012; La Felice and Landi 2011b; Di Stefano et al. 2020; Andronico et al. 2021), and carried off by the magma during its ascent toward the surface. Based on the habit, euhedral rims of clinopyroxene crystals with Mg# 0.82–0.86 (Fs8–10) associated with olivine rims Fo81–82 seem to be in textural equilibrium with a matrix glass with K2O = 2.6–2.7 wt.% (Mg# 0.50). Similarly, olivine Fo81–82 is in chemical equilibrium with the glass K2O = 2.6–2.7 wt.% (Mg# 0.50), the anorthite content in the experimental plagioclase, including plagioclase–melt interaction experiments presented in Pichavant et al. (2022), is always lower than An90 (An ≤ 85 mol.%), although the equilibrium residual melts have intermediate composition with K2O between 2.6 and 3.5 wt.% that encloses the 19 July 2020 glass compositions. Based on the experimental results, we can infer that the magmas with intermediate composition hosting plagioclase An87–91 emitted during the 19 July 2020 major explosion resided in the lower part of the intermediate zone of the plumbing system that extends between 100 MPa and the bottom of the HP magma body (~50 MPa). The texture at the cores of the An-rich microphenocrysts (Fig. 4e, f) differs from the “reaction textures” found in the mineral/melt interaction experiments, for the occurrence of large bubbles and large melt inclusions, and is better explained with a rapid growth under degassing (Landi et al. 2004). Therefore, the crystallization of microphenocrysts of plagioclase was maybe favored by an event of rapid nucleation under decompression from LP melt storage zones to ~50–100 MPa (2–4 km) (growth of patchy zoned, bubble-rich cores An70–90), followed by the crystallization of An90 plagioclase at nearly equilibrium conditions. Using growth rate ($G_0$) values of $10^{-7}$–$10^{-8}$ cm/s calculated by Agostini et al. (2013) for plagioclase, the residence time

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necessary for 100 μm An₉₀ microphenocrysts (Fig. 4e, f) to grow ranges from ~1 to 11 days. These must be considered as minimum values because GL was experimentally obtained under decompression, thus at relatively high undercooling and rapid growth.

**Petrogenetic processes and melts evolution**

The origin of the compositional variations measured in matrix glasses was investigated by Rayleigh fractional crystallization equations and mass balance calculations using PETROMODELER excel spreadsheet (Ersoy 2013) for the trace element composition. The partition coefficients \( K_D = \frac{C_{\text{mineral}}}{C_{\text{melt}}} \), where \( C \) is the concentration in ppm) for clinopyroxene, olivine, and plagioclase in equilibrium with LP, intermediate, and HP melts, were calculated using average composition of the matrix glasses, and the rims of phenocrysts (Table 3; Online resource 1). The resulting partition coefficients obtained in this work fall in the range of mineral/melt \( K_D \) obtained in experiments and for phenocryst/matrix pairs (GERM database: https://earthref.org/KDD-old/). The only exception concerns Chromium, which is one order of magnitude higher for the clinopyroxene in equilibrium with LP melts (Fs₅ in Tables 2 and 3). Although trace element data on cpx Fs₅-₈ are not available from the literature, we consider this result realistic since minerals in equilibrium with HP analyzed in this work have trace element content fully comparable with data published on products with similar composition (Ubide et al. 2019) and also because, in both the analytical sessions of 2001 and 2021, the cpx Fs₅-₈ have a Cr content within the same range of variation (3800–5080 ppm, Online resource 1).

**Table 3** Partition coefficients \( (K_D) \) of selected trace elements between mineral and matrix glasses of the LP, intermediate and HP products. Mineral and matrix glasses composition in equilibrium are the same reported in Table 2.

| Element | LP products from paroxysms | Intermediate products from 19 July 2020 | HP products from all eruption styles |
|---------|-----------------------------|---------------------------------------|-------------------------------------|
|         | Ol (Fo86)                   | Cpx (Mg#0.87)                         | Ol (Fo67.1)                         |
|         |                             |                                       | Pl (An₉₀)                           |
|         |                             |                                       | Matrix glass                        |
|         |                             |                                       | \( K_D^{ol} \)                       |
|         |                             |                                       | \( K_D^{cpx} \)                       |
|         |                             |                                       | \( K_D^{pl} \)                       |
| Ba      | bdl                         | n.d                                   | 851                                 | <0.0001              | n.d                   | 0.117                  |
| Sr      | <0.0001                     | 58                                    | 667                                 | <0.0001              | 0.09                  | 1.93                   |
| Th      | bdl                         | 0.07                                  | 11.4                                | <0.0001              | 0.006                 | <0.0001                |
| Zr      | bdl                         | 12                                    | 126                                 | <0.0001              | 0.1                  |
| Cr      | 36.45                       | 3604                                  | 18.1                                | 2.0                  | 199                   |
| Ni      | 1193                        | n.d                                   | 40                                  | 29.8                 | n.d                   |                       |
| Nd      | bdl                         | 8.6                                   | 34.1                                | <0.0001              | 0.25                  |                       |
| Ba      | bdl                         | 0.29                                  | 124.02                              | <0.0001              | 0.0002                | 0.117                  |
| Sr      | bdl                         | 45.23                                 | 1189.80                             | <0.0001              | 0.07                  | 1.93                   |
| Th      | bdl                         | 0.10                                  | 17.32                               | <0.0001              | 0.006                 | <0.0001                |
| Zr      | bdl                         | 31.74                                 | 0.21                                | <0.0001              | 0.18                  | 0.001                  |
| Cr      | 12                          | 530.73                                | 9.27                                | 1.3                  | 57                    | <0.0001                |
| Ni      | 677                         | 155.68                                | 2.40                                | 26.8                 | 6.1                   | 0.095                  |
| Nd      | bdl                         | 12.35                                 | 1.17                                | <0.0001              | 0.27                  | 0.03                   |

\( \text{Fo} = \text{Forsterite}, \text{Mg}\# = \text{MgO}/(\text{MgO} + \text{FeO}), \text{An} = \text{Anorthite mol.\%}, \text{ol} = \text{olivine}; \text{cpx} = \text{clinopyroxene}; \text{pl} = \text{plagioclase} \)

*Average analysis from Landi et al. 2004
LP melts

The LP magma deep system has been the object of several works in the past decades that point to a model represented by a dyke-like feeding system that extends between 6 and 9 km, characterized by repeated refilling from depth followed by magma mixing, minor crystallization of mafic minerals and assimilation of deep cumulates (Pichavant et al. 2009, 2011; Schiavi et al. 2010; Pompilio et al. 2012; Métrich et al. 2010, 2021).

In our data set, the pumice from the 15 March 2007 paroxysm shows the higher content of Cr (Cr > 24 ppm), the LP products erupted on 5 April 2003 and 3 July 2019 paroxysms have low Cr contents (Cr < 20 ppm), and products of the 28 August 2019 paroxysm have intermediate Cr values (Figs. 5d). We point out that among the violent explosions analyzed, the paroxysms with highest intensities are fed by Cr-poor magmas that are possibly less contaminated by processes of cumulate assimilation. This aspect, out of the scope of the present work, needs to be further investigated to establish if the highest intensity paroxysms associated with lower cumulate assimilation (low Cr) can be related to fast magma ascent from deep sources.

Another relevant point concerns the compositional differences observed in the erupted tephra emitted during major explosions and paroxysms (Figs. 5, 7) that were also detected by Pioli et al. (2014), based on the major element analyses of the matrix glass. In the diagram Th/Nd vs Th (Fig. 7a) the less evolved glasses, corresponding to samples from paroxysms with $K_2O < 2.1$ wt.%, follow a mixing line between the less and more evolved end-members with Th 9.3 ppm and 11.6 ppm, respectively, where the glasses from 3 July 2019 occupy the field at highest values (10.3–11.6 ppm). Conversely, the chemical variations measured in the 28 August 2019 paroxysm and the major explosions deviate from the mixing line, and are well fitted by a model of fractional crystallization, explained by less than 15 vol.% of cpx (± ol), starting from LP glasses erupted in paroxysms with variable Th/Nd ratios (Fig. 7b). However, the differences in Cr and Ni content in the matrix glasses of pumiceous LP products are not consistent with a simple crystal fractionation of clinopyroxene and olivine. These variations, which were associated with different extents of assimilation of gabbroic cumulates at depth (Pichavant et al. 2009; Schiavi et al. 2010), combined with crystal fractionation, seem to persist even in the products of major explosions following the paroxysm. In fact, after 2007, the two major explosions of November 2009 are perfectly aligned with the evolutionary trend starting from the LP products emitted on 15 March 2007, and similarly, the Cr and Ni contents of the glasses erupted on the 19 July 2020 major explosion have intermediate values between the LP pumices of the 2019 paroxysms and the field of variation of HP glasses from the normal activity (Fig. 7b). Considering that there is not a clear relationship between the bulk rock composition and the intensity of the explosion (Pompilio et al. 2012; Métrich et al. 2021), the evolved glasses found in LP products from major explosions should be related to a higher crystal content of the magma, likely induced by lower volatile contents/
lower temperature at relatively lower pressure. Although the LP products are generally crystal poor, small differences in the degree of melt evolution due to crystallization among the erupted products are consistent with the results from melt inclusions in olivine that point to a vertical and chemical zoning of the deep feeding system (Bertagnini et al. 2003; Métrich et al. 2010). Moreover, the chemistry of the matrix glass agrees with the lower content of Fo (mol.%) in the outer rim of the olivine from major explosions compared to those of the paroxysms (Métrich et al. 2001, 2021).

The depth of the LP reservoir is reported at 190–250 MPa (about 6–9 km), based on the total fluid pressure \( P_{\text{H}_2\text{O} + P_{\text{CO}_2}} \) recorded by melt inclusions (Métrich et al. 2010, 2021). \( \text{H}_2\text{O} \) and \( \text{CO}_2 \) have been measured only in melt inclusions hosted in olivine from pumices erupted during paroxysms (both small and large), so it cannot be excluded that the LP feeding system can extend at a relatively shallower depth. Since LP magmas are distinct from intermediate or HP magmas by the absence of plagioclase, following the previously discussed experimental results, the top of the LP reservoir might be located at a pressure up to 100 MPa. We propose that the LP deep reservoir develops a vertical zoning in terms of chemical compositions of the liquid phase and crystal content, producing a slightly more evolved cap, or pockets of more evolved magma located in the upper portion of the deep feeding system. During the paroxysms, the gas-rich magma rises from the deepest portions of this dike-like reservoir, while major explosions are suggested to involve only the shallower portions. Alternatively, the magma feeding the major explosions can represent the feeding zone of the HP reservoir, which is continuously hybridized by regular arrivals of the LP magmas, as suggested by Pioli et al. (2014). However, the continuum evolutionary trend modeled by simple fractional crystallization, starting from the LP melts found in paroxysms, is in better agreement with the suggestion of a vertical zoned LP reservoir. Here, minor degassing, possibly accompanied by a small decrease in the temperature, can induce minor crystallization of mafic minerals. Additional studies focusing on these evolved LP magmas are necessary to better position and define the upper part of the LP reservoir.

**Intermediate melts**

The large variability measured within the studied glasses with intermediate compositions between LP and HP end-members can be ascribed to different petrogenetic processes, with particular reference to mixing and mixing + crystallization. In the \( \text{CaO/Al}_2\text{O}_3 \) vs \( \text{FeO/MgO} \) diagram, intermediate compositions measured in samples from the 8 November 2009 major explosion cover the whole range between the two end-members (Fig. 8a). As shown in previous studies focused on this eruption, these intermediate compositions
can be interpreted mostly as magma mixing at different degrees of hybridization (La Felice and Landi 2011a; Andronico et al. 2021; Pioli et al. 2014). Trace element modeling indicates that they can be approximated by mixing processes (Fig. 8b, c), in particular between Cr-rich melts, as that erupted on 15 March 2007, and HP melts (Fig. 8b). Conversely, the relatively evolved intermediate compositions measured in the products of the 9 January 2005 high-energy explosion have been interpreted as related to mixing and/or mineral dissolution due to rehydration of the sinking HP degassed magma and its re-equilibration at higher water pressure (Landi et al. 2008; Pioli et al. 2014). The scattered Cr and Ba contents in glasses from 9 January 2005 shown in Fig. 8 agree well with the invoked process of mineral dissolution.

In Fig. 8a the intermediate glasses of the products erupted on the 19 July 2020 major explosion deviate from the mixing lines, following a trend parallel to the CaO/Al2O3 axis (between CaO/Al2O3 0.51–0.56 and FeO/MgO 1.6–1.8). A few lapilli erupted in a recent major explosion that occurred on 6 October 2021 (only major element composition available) have a glassy matrix with nearly homogeneous and intermediate compositions close to that of the 19 July 2020 products (CaO/Al2O3 0.53–0.57; FeO/MgO 1.7–1.8; K2O 2.5–2.8 wt.%) that line up on the same trend. A parallel trend was previously detected in the products erupted during the historical, large paroxysm that occurred in the sixteenth century (Fig. 8a) (Bertagnini et al. 2011; La Felice and Landi 2011b). In this case, the horizontal trends start from LP compositions and are related to clinopyroxene crystallization (La Felice and Landi 2011b). Chemical modeling indicates that the 19 July 2020 intermediate glasses can be reproduced by superimposing mixing processes and fractional crystallization (Fig. 8b, c), where the LP end-member involved is likely similar to that erupted on 5 April 2003 and 3 July 2019 paroxysms, in terms of Cr and Ni content (Fig. 8a). More in detail, in Cr vs Th diagram, results of Rayleigh crystallization, performed using the K_{D} of intermediate mafic paragenesis, indicate that less than 10 wt.% clinopyroxene and olivine drive the residual melts to the 19 July 2020 intermediate glass domain (Fig. 8b). The trend of variation of Ba/Zr vs Ba suggests that the intra-eruption glass variability can be accounted by a < 15 wt.% of crystallization that involves mainly pl and cpx ± ol, in variable proportions (Fig. 8c). Accordingly, plagioclase starts to become the dominant mineral phase in these intermediate melts, as confirmed by the occurrence of euhedral microphenocrysts of anorthite-rich plagioclase.

It should be noted that in all the graphs presented, a more or less significant dispersion of the points plotted is observed. Indeed, the whole feeding system at Stromboli, from the deep LP reservoir to the shallow conduits, is largely dominated by mixing processes due to continuous refilling and degassing (Landi et al. 2004, 2008; Métrich et al. 2021). According to Perugini et al. (2006, 2008), extensive and continuous chaotic mixing may induce a “diffusive fractionation” process leading to melts heterogeneity and large dispersion of the trace element values. Dispersion can be also produced by local enrichment/depletion of trace elements due to disequilibrium crystallization during ascent and degassing.

**HP melts**

The HP glasses analyzed fall within a rather narrow chemical interval, K_{2}O 3.9–4.4 wt.% and CaO 6.8–7.8 wt.% (Fig. 9a). The observed systematic differences, both in major and trace elements, of the HP scoriae emitted during explosions with different intensities, can be modeled with a minor extent of crystallization (<20%) of a solid composed of the same minerals observed as modal crystals, in which plagioclase dominates over mafic minerals and vice versa (Fig. 9b, c), depending on how much cooling (plus clinopyroxene and olivine) or degassing (plus plagioclase) affect the crystallization process. Indeed, the P–T field of stability of cpx in basaltic magmas covers a lower and wider temperature range than plagioclase (Bamber et al. 2020). Interestingly, HP glasses mingled with LP material in products from paroxysms show the more evolved compositions, as also highlighted by the comparison with major element analyses of products from the normal activity between 2005 and 2008 (Landi et al. 2011). This is consistent with the involvement of large portions of the shallow HP reservoir during the high-energy paroxysmal activity, including also the cooled and crystallized portions at the conduit walls.

Another important consideration concerns the Cr and Ni content of HP products. In the diagram Ni vs Cr (Fig. 7b), the Cr-rich and Cr-poor trends, depicted by LP and intermediate magmas, converge into a rather tight HP area, where the different Cr contents of glasses with a comparable evolutionary degree are no longer recognizable. Continuous refilling, crystallization, and mixing within the shallow system can obliterate, in the residual matrix glass, the geochemical fingerprints of the primary magmas.

**Insights into the magmatic plumbing system**

The results discussed above are in agreement with a dike-like magma system that evolves from the deep, volatile-rich LP to the shallow, volatile-poor HP end-members through several petrogenetic processes, among which mixing and crystallization play the main roles. The compositional characteristics of the products erupted during the different styles of activity allow the reconstruction of a vertically zoned plumbing system, in terms of matrix glass composition, glass heterogeneity, and crystal content and composition.
(Fig. 10). An accepted model of the LP portion of the plumbing system indicates that the magma involved in the paroxysms of the past two decades is located at a depth between 6 and 9 km, and its compositional fingerprinting derives from mixing processes, likely due to refilling from depth and self-mixing (Métrich et al. 2021). The data set presented in this work offers the opportunity to improve some aspects of the petrogenetic evolution of the deep feeding system. In particular, we suggest that the LP end-member erupted during major explosions derives from the upper portion of the LP reservoir, where magmas become more evolved, due to crystallization of mafic minerals, rather than mixing. During major explosions, this evolved LP end-member commonly erupts together with intermediate magmas residing in the intermediate zones of the feeding system. The intermediate zone is typified by a strongly dynamic petrogenetic evolution dominated by mixing and crystallization processes that transform the LP magma into the HP one. The products from the 19 July 2020 major explosion point to almost equilibrium crystallization in small magma pockets that, before entering into the HP reservoir, remain nearly isolated for a maximum of 11 days, likely in the lower part of the intermediate zone where a highly calcic plagioclase crystallizes. Indeed, this gives a snapshot of the depth in the plumbing system at
which the crystallization of the plagioclase begins. In the HK basaltic magma currently emitted at Stromboli, plagioclase crystallization as a result of degassing becomes a dominant process at very shallow levels to produce the HP magma (plagioclase ~ 66 vol.% of the mineral phases). The largely hybridized zone of the plumbing system is located in the upper part of the intermediate reservoir, where mixing between the HP body and the residing magma, also due to sinking phenomena of the dense HP magma, should be favored. The 9 January 2005 high-energy explosion that erupted intermediate, rather evolved and strongly inhomogeneous melts, with no LP end-member (Landi et al. 2008; Pioli et al. 2014), was likely fed by these strongly hybridized magmas. A relevant conclusion of the above reasoning is that at Stromboli there is a correlation between the magnitude of the explosive events and the depth from which the

![Fig. 10 Schematic representation of the vertically extended magmatic system that feeds the persistent activity at Stromboli volcano. The yellow tones represent the LP magma, the green tones the intermediate magma (INT) and in black the HP magma. The portions of the plumbing system involved in the different types of explosive activity, from normal explosions to paroxysms, are indicated on the right. The large-scale paroxysms of Métrich et al. (2021) are non-represented. Extensive sin-eruptive mixing during major explosions and paroxysms does not allow to discriminate between intermediate melts produced during mixing and those coming from the intermediate zone of the plumbing system (dashed lines). The depth of the different zones of the plumbing system is in part taken from Métrich et al., 2021 (deep LP reservoir), in part are derived from the comparison between the mineralogical characteristics of the products and data from experimental petrology (see text for more explanations)](image-url)
magma rises (Fig. 10). According to Schiavi et al. (2010), the different Cr content observed in LP products from paroxysms suggests that the high-Cr melts may have traveled slower within the deep conduits resulting in a longer time of interaction, and thus assimilation, with the deep crystal mush.

Although pumices with intermediate matrix glass were detected among the products erupted between 1998 and 2020, intermediate petrochemical characteristics similar to that observed in the 19 July 2020 vesicular material had never been found. A small quantity of vesicular lapilli with nearly homogeneous, intermediate glasses were erupted about 15 months later, on 6 October 2021. This raises the question of whether the sampling intensification carried out in the last two years (within UNO Project—INGV Departmental Strategic Projects) enabled the collection of products that are present in low quantities, or whether this material was truly absent in the activity of the past decades, thus heralding some changing in the volcano’s feeding system. The answer to this delicate question relies on the intensification of product sampling of future eruptions, and more detailed glass analyses of pumice erupted in historical times.

Conclusive remarks

Systematic major- and trace element analyses of the matrix glasses in pumices and scoriae emitted in the past two decades at Stromboli yielded insights into some aspects regarding the chemical evolution and compositional zoning of the plumbing system.

In the following, we listed the main results in which the three chemical groups (LP, Intermediate, and HP magmas) are linked to the plumbing system architecture:

- data highlight small, but significant chemical differences between the products erupted in major explosions and paroxysms, being the glassy matrix in pumices from major explosions slightly more evolved (about <15 wt.% of cpx + ol crystallization). This points to a vertical chemical zoning of the deep LP reservoir and indicates that major explosions are fed by magmas that rise from the upper portions of the LP system, while the deeper portion of the LP reservoir is only involved during the paroxysms;
- the occurrence of primary magmas with different Cr content is confirmed. Among the studied eruptions, the most energetic paroxysms (5 April 2003 and 3 July 2019) are associated with Cr-poor magmas;
- among the products erupted between 1998 and 2020, intermediate products with a rather homogeneous matrix glass carrying microphenocrysts of plagioclase An₉₀ have been sampled for the first time. These samples give a snapshot of a pocket of magma that remains locally isolated few days in a dike-like system, at a depth of 100–50 MPa where the plagioclase crystallization and thus the real transformation from LP to HP magmas begins. With pressure decreasing, volatile loss inducing plagioclase crystallization, magma mixing, and hybridization phenomena become more and more extensive up to the formation of the crystal-rich, shallow HP magma;
- the small compositional differences in the HP matrix glasses are linked to a moderate degree of crystallization. The variability of Cr and Ni contents observed in LP and intermediate magmas is no longer recognizable in the residual matrix glass due to continuous mixing, degassing, and crystallization within the shallow reservoir;
- compositional variations between the products erupted in the different types of explosive activity at Stromboli indicate a relationship between the magnitude of the explosions and the depth of the supply magma. This interpretation, if confirmed by future eruptions, could represent an important step forward to understanding the dynamics of the pre/syn-eruptive magma that drives the volcano’s calamitous events, to be compared also with geophysical and geochemical data.

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