



Magma storage, evolution, and degassing at Mombacho (Nicaragua): New insights to decipher the current state of activity of a long-dormant volcano

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ABSTRACT

The Mombacho is a basaltic-andesitic composite volcano of Nicaraguan Quaternary volcanic chain. As no historical eruption has been recorded at Mombacho, there is no available information about the depth of potential magma storage zones, or about the evolution of ascending magmatic fluids. However, this information is urgently needed given the current state of the volcano, which is showing signs of unrest. To acquire this knowledge, melt inclusions and pyroxene crystals in various Mombacho tephra were analyzed, along with the volcanic gases emitted by fumaroles in the crater. The major element compositions of the melt inclusions support, to a first order, a magmatic evolution controlled by the fractional crystallisation of olivine, pyroxene, plagioclase and titanomagnetite crystals. However, the compositional variability of the most mafic samples can only be explained by a source heterogeneity. Additional trace element analyses agree with this hypothesis but seem to highlight a migration of the most mobile elements with an aqueous phase. The composition of the clinopyroxene crystals and the H₂O and CO₂ contents of the melt inclusions reveal the presence of a complex main storage zone between 8.2 ± 1.6 and 3.1 ± 0.4 km. Degassing modelling also supports this architecture and indicates that the gases sampled in 2024 in the Mombacho fumarole come from depths similar to this large storage zone. In addition, the 2024 fumarole gas contents in SO₂, H₂O and CO₂ are similar to those sampled around twenty years ago, highlighting the stability of the degassing and therefore of the underlying magmatic system.

1. Introduction

In a world where volcanic eruptions are an important natural hazard in many regions (Oppenheimer, 2015), long-dormant volcanoes play a special role. On the one hand, the lack of collective memory of the eruptive activity and the fertility of the volcanic soils (Fiantis et al., 2019; Cook et al., 2022), which enable significant socio-economic development, allow these areas to become densely populated. On the other hand, long periods of quiescence can encourage the accumulation of energy at depth and lead to violent eruptions (Chiodini et al., 2016). Furthermore, monitoring networks are rarer in these long-dormant worldwide areas and knowledge about the past activity of volcanoes is often lacking, thereby increasing the volcanic hazard (Boudoire et al., 2023). So, in order to limit the hazard and to be able to see and

understand potential changes in activity, it is crucial to understand how these quiescent volcanoes work, starting with their past activity. In order to provide a partial answer to this issue, melt inclusions have emerged as a powerful tool (Cannatelli et al., 2016). These droplets of silicate liquid trapped in crystals can be used for studying and understanding the origin and evolution of the magmas involved in the previous eruptions, and therefore for understanding the past dynamics of the system and identifying storage zones. Since the early 1990s, they have been used to discuss magma evolution (Kent and Elliott, 2002; Venugopal et al., 2016; Gennaro et al., 2019) pre-eruptive volatile element composition (Metrich and Wallace, 2008; Moore, 2008; Zurek et al., 2019), degassing processes (Metrich and Wallace, 2008; Hartley et al., 2014; Metcalfe et al., 2023) and magma storage depths (Iacono-Marziano et al., 2012; Ghiorso and Gualda, 2015; Allison et al., 2019). Coupled with the study

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of clinopyroxene crystals, which also provide information on magma storage depths (Putirka, 2008), they can be used to decipher the architecture of magmatic systems related to past volcano activity (Venugopal et al., 2016; Métrich et al., 2010; Robidoux et al., 2017a; Robidoux et al., 2017b). These constraints can then be used to construct hypotheses about their future activity and to see and understand potential changes.

The Mombacho volcano in Nicaragua is one of those dormant edifices for which no historical eruption has been documented (McBirney and Williams, 1965) and whose past activity and the architecture of its magmatic system are unconstrained. However, in recent years the volcano has shown signs of unrest (cf. bulletins from Instituto Nicaragüense de Estudios Territoriales (INETER; <https://web-geofisica.ineter.gob.ni/vol/dep-vol.html>)), challenging the dormant nature of Mombacho and threatening the surrounding villages as well as the historic (and touristic) town of Granada (population 131,000). Given the current state of the volcano, it is essential to understand the past activity of the edifice as well as the evolution and storage conditions of the magma.

In this study, melt inclusions and clinopyroxene crystals are used to constrain (1) the evolution of the Mombacho magmas, (2) the architecture of the magma storage system and (3) degassing processes. Based on these data, a conceptual model is proposed. The geochemical signature of gas emissions currently emitted in the fumarolic field are compared to this model to give insights into their origine and finally, to provide information on the current state of activity of Mombacho.

2. Geological setting

2.1. Regional geology

On the Pacific coast of Nicaragua, along the Central American Trench, the Cocos Plate is subducting beneath the North American and Caribbean plates (Fig. 1a). This subduction is at the origin of the Central American Volcanic Front (CAVF), which stretches from Guatemala to Costa Rica (Stoiber and Carr, 1973). Along the CAVF, the geometry of the subduction and the structure of the crust and upper mantle vary, resulting in several blocks (Stoiber and Carr, 1973; Carr, 1984). The continental block on which Nicaragua is located differs from the others in two main ways: (1) it has the steepest dips (75–80°; (Protti et al., 1994)) for a convergence rate of around 8 cm/year (DeMets, 2001) and (2) the continental crust is thinner. These differences, in addition to extensional oblique regional faults path (Walker, 1984; Van Wyk De Vries et al., 2007; La Femina et al., 2002; Higgins et al., 2022), are thought to explain the low altitude of Nicaraguan volcanoes and the less differentiated nature of their magmas (Carr, 1984; McBirney, 1969).

Volcanic activity in Nicaragua is characterized by a significant period of magma production that took place in the Quaternary, giving rise to a major volcanic chain (McBirney and Williams, 1965). Nicaragua's Quaternary volcanic chain crosses the country along a north-west/south-east axis (Fig. 1c). Located in the Nicaraguan depression, this chain comprises two main segments: the Cordillera de los Marabios and the volcanoes between Lake Managua and Lake Nicaragua (Fig. 1c). The Cordillera de los Marabios stretches along the south-western edge of the depression and comprises twelve volcanic centers, including San

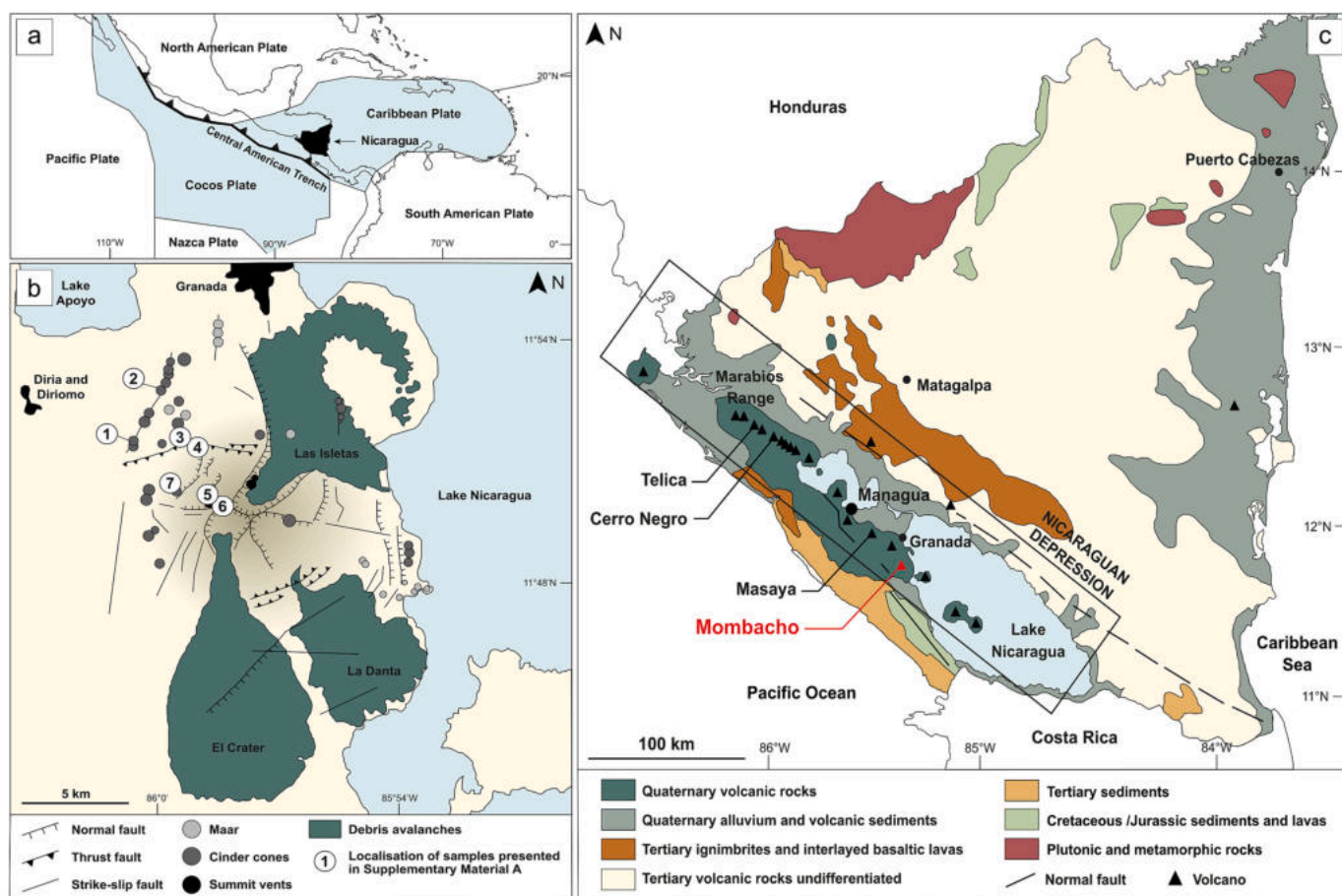


Fig. 1. a. Subduction zone of Central America and Nicaragua location along the Central American Trench. b. Simplified structural and geological map of the Mombacho volcano, modified from Shea et al. (Shea et al., 2008). c. Simplified geological map of Nicaragua, modified from McBirney and Williams (McBirney and Williams, 1965).

Cristóbal, Telica, Cerro Negro and Momotombo active volcanoes (Fig. 1c). The products emitted by these centers are mainly basalts and andesitic basalts (Venugopal et al., 2016; Robidoux et al., 2017a; Robidoux et al., 2017b; McBirney and Williams, 1965; Tramontano et al., 2025). Further south, between Lake Managua and Lake Nicaragua, lies the second segment with about ten volcanic centers, including the persistently active Masaya volcano and Mombacho (Fig. 1c). Unlike the Cordillera de los Marabios, this alignment displays complex morphological (cones, craters, calderas, domes), petrological and geochemical (basalts, andesites, dacites) variability (McBirney and Williams, 1965; Hlinka et al., 2021). Furthermore, among the mafic members of this segment, two major series can be distinguished (Walker, 1984; Walker et al., 1990): magmas with low titanium content (low-Ti) and magmas with high titanium content (high-Ti). It is also possible to find magmas that are a mixture of these two extremes. According to Walker et al. (Walker et al., 1990), the products of the two series come from intrinsically different sources, with the low-Ti magmas showing a greater influence from the pelagic sediments of the plunging plate.

2.2. Mombacho volcano

Mombacho is a 1345 m-high composite volcano located on the north-western shore of Lake Nicaragua, around 10 km south of the town of Granada (Fig. 1b). It is a Quaternary volcano resting on the Tertiary-age ignimbrites of Las Sieras and Apoyo (Fig. 1c). Although previously considered dormant (McBirney and Williams, 1965; Weyl, 1980), the current morphology of the edifice and the surrounding volcanic deposits testify to a complex past (Fig. 1b). At least three major flank collapses are responsible for the volcano's current shape (Van Wyk De Vries and Francis, 1997; Shea et al., 2008). At the summit, the scars from two of these collapses form amphitheatres from which the debris avalanches started (Fig. 1b). One is open to the north-east and is at the origin of the debris avalanche known as Las Isletas. The other, at the origin of the El Crater debris avalanche, is open to the south and contains a fumarolic field (Van Wyk De Vries and Francis, 1997). A study of the structure of these avalanches and an analysis of the facies revealed that the collapses were not of volcanic origin but were linked to a change in the hydrothermal system in the case of El Crater and to gravity spreading in the case of Las Isletas (Shea et al., 2008). The Las Isletas debris avalanche is dated at ~1700 BP (~140 to 345 A.D.) and the El Crater one at ~1300 BP (~270 to 650 A.D.) (Stansell, 2013). Deposits from a third debris avalanche, called La Danta, are visible to the south-east of the edifice, but the scar from the collapse is covered by other products (Shea et al., 2008).

During its eruptive phase, Mombacho mainly emitted basaltic to andesitic lava flows, although products of dacitic composition were emitted later in the form of domes (McBirney and Williams, 1965). In a SiO_2 vs. $\text{K}_2\text{O} + \text{Na}_2\text{O}$ diagram (cf. TAS), these magmas describe a calc-alkaline series characteristic of subduction zones. Gas analysis of the fumaroles in the El Crater amphitheatre has revealed the presence of SO_2 , H_2S , HCl and HF , indicating a significant contribution of magmatic fluids in the current hydrothermal system (Garofalo et al., 2007). In the early 2000s, this hydrothermal system was stable (Garofalo et al., 2007). However, the extension and intensification of degassing since 2017 raises the need to repeat analyses of these gases today. In addition, these changes in the fumarolic field activity are accompanied by volcano-tectonic earthquakes and damage to the summit vegetation [INETER, personal communication]. These observations indicate a modification of the Mombacho system or a destabilization.

3. Methods

3.1. Samples

The sampling strategy was to collect both mafic and evolved melts to constrain potential district part of the system. In the absence of single

outcrop able to address this strategy, we had to collect at multiple sites (Fig. 1b) despite the absence of chronological information. Eleven rock samples were collected during field campaigns in 2022 and 2023. All samples were analyzed for major elements. However, only five were selected for melt inclusion and clinopyroxene crystal investigations: MBQ1, MBQ2B, MBQ2L2, MBT2 and MBT1. They were chosen because there are tephras, which ensures rapid quenching of the products and therefore better preservation of the melt inclusions. For these five samples, melt inclusions were selected. They are hosted by crystals of olivine for MBQ1, olivine and clinopyroxene for MBQ2B and MBQ2L2, olivine, clinopyroxene and plagioclase for MBT2 and orthopyroxene and plagioclase for MBT1.

Samples were crushed using the BB 250 XL Retsch jaw crusher at Laboratoire Magmas et Volcans (LMV). The crushed pieces were then sieved to obtain four fractions of different sizes: <500 μm ; 500 μm –1 mm; 1–2 mm; >2 mm. The 500 μm –1 mm fraction is the one containing the most crystals and is therefore retained for the following steps. Within this fraction, olivine, clino- and orthopyroxene and plagioclase crystals were sorted manually with a binocular microscope before being placed on a slide to identify melt inclusions. After an initial rough polishing on a silicon carbide mat to make the grains more transparent, each crystal was observed under the microscope. Those containing primary melt inclusions, far from the crystal rim and without visible microcrystals, were selected and then repolished one by one in order to bring the inclusions to the surface using mats with 6, 3 and then 1/4 μm diamond suspensions. Finally, the crystals containing the selected and prepared inclusions were mounted on epoxy resin blocks before being analyzed by Raman spectroscopy, electron microprobe and laser ablation inductively coupled plasma mass spectrometry. Some melt inclusions were double polished to enable analysis by Fourier Transform Infrared (FTIR) spectroscopy. Polished thin sections of the five samples selected for petrological investigations were also prepared for analysis of clinopyroxene crystals.

3.2. Analytical methods

3.2.1. Inductively coupled plasma optical emission spectrometer (ICP-OES)

The major elements of whole rocks were analyzed using an Agilent 5800 ICP-OES at LMV. Before analysis, two water losses on ignition (LOI) were carried out, one at 110 °C and the other at 1100 °C. A basaltic composition standard and a dacitic composition standard were run at the beginning, middle and end of the analysis sequence (Supplementary Material B, Table B.1). The associated average errors (2σ) are 0.7 wt% for SiO_2 , 0.02 wt% for TiO_2 , 0.16 wt% for Al_2O_3 , 0.24 wt% for Fe_2O_3 , 0.003 wt% for MnO , 0.20 wt% for MgO , 0.29 wt% for CaO , 0.02 wt% for Na_2O and 0.01 wt% for K_2O and P_2O_5 .

3.2.2. Raman spectroscopy

The melt inclusions of the five samples selected for analysis were first analyzed by Raman spectroscopy using the Renishaw inVia Raman at LMV to determine the H_2O content dissolved in the glass. Some groundmasses and an embayment were also analyzed. The Raman micro-spectrometer is equipped with a 532 nm diode-pulsed solid-state laser (200 mW output power), a Peltier-cooled CCD detector of 1024×256 pixels and a Leica DM 2500 M optical microscope. Laser power was reduced below 6 mW on the samples to avoid damage. The spectra were acquired over the 100–1200 cm^{-1} window corresponding to the vibrational frequencies of the silicate network and over the 3000–3800 cm^{-1} window corresponding to the O–H vibrational frequencies (water band). After acquisition, spectra contaminated by the host mineral signal were corrected when possible, and then a cubic baseline was subtracted from all spectra using PeakFit software. The absolute intensities of the resulting water band were then normalized to counting time and laser power, and converted to concentration based on the linear relationship defined by the standard glasses. In total, twelve standards with compositions ranging from basalts to rhyolites were

analyzed at the beginning, middle, and end of the analytical sessions. For water quantification, both internal and external calibration methods were carried out (Behrens et al., 2006; Mercier et al., 2009; Schiavi et al., 2018). The water concentration values presented here are those obtained using the external calibration, because in some spectra it was not possible to eliminate the signature of the host mineral from the silicate network spectral region before applying the internal calibration. When both external and internal calibration procedures worked well, the determined water concentrations generally matched within 5% difference (1 RSD). The average concentration error is 0.2 wt% (2σ). For melt inclusions whose spectra indicated the presence of a micro-crystallized hydrated mineral phase, the absolute intensities of the O–H band of the glass phase for water could not be determined. Consequently, their H₂O content could not be quantified.

Some bubbles contained in the melt inclusions were also examined in order to identify the presence of solid or fluid species. For this purpose, the spectra were acquired over an extended window ranging from 60 cm⁻¹ to 4300 cm⁻¹, allowing the Raman peaks of species such as sulfides, sulfates and carbonates, and liquid water to be seen.

A 3D Raman tomography of a bubble was also carried out using the Renishaw inVia Kontor Raman from the Institut de Chimie de Clermont-Ferrand (ICCF), also equipped with a 532 nm diode-pulsed solid-state laser (100 mW output power), a Peltier-cooled CCD detector of 1024 × 256 pixels detector and a Leica confocal optical microscope, using a x100 objective. 3D mapping produced a single hypermap of about fourteen thousand spectra in the X-Y-Z space. Acquisitions were collected with a sampling step distance of 1 μm in the three directions and acquisition time was 15 s/point. The Renishaw's WiRETM software recorded the spectra in the 190–1340 cm⁻¹ wavenumber range, which contains the main vibrational modes of CO₂, carbonates, sulfates and sulfides. After acquisition, a polynomial baseline was subtracted from all the spectra using PeakFit software. For each phase present inside the bubble, a representative peak was selected. And a 3D distribution map of the peak intensity was created by setting a threshold of intensity for each selected peak (Schiavi et al., 2020). Then, by manually redefining, plane by plane, the contours of the species detected in the bubble are manually redefined so as to induce as little error as possible. Once the entire bubble with its component species was reconstructed, the area occupied by the different species was calculated using ImageJ software and then integrated over the entire volume of the bubble (see Schiavi et al. (Schiavi et al., 2020) for further details about the method). Finally, the volumes were converted into concentration, with the associated final errors (2σ) being 1100 ppm for CO₂ stored as carbonates and 40 ppm for S stored as sulfides.

3.2.3. Fourier transform infrared spectroscopy (FTIR)

As the CO₂ content of the glassy part of melt inclusions was too low to be detected by Raman spectroscopy, some of them were analyzed by FTIR spectroscopy, which has a lower detection limit. For CO₂ and H₂O quantification, twelve melt inclusions were double-polished and analyzed at LMV using a Bruker Vertex 70 spectrometer coupled with a Hyperion microscope system, a KBr beamsplitter, a MCT detector and a CaF₂ window. When possible, melt inclusions with and without a shrinkage bubble were selected in order to estimate the percentage of volatiles migrated into the bubble at the time or after its formation (Moore et al., 2015). The spectra were recorded in the range 700–7500 cm⁻¹ range, including the O–H band of water and the two peaks of CO₃²⁻ species dissolved in the glass. After acquisition, spectra showing contamination by atmospheric CO₂-H₂O were corrected and all spectra obtained underwent baseline correction via the OPUS software. In this way, the intensity of water and CO₃²⁻ bands could be used in Eq. (1):

$$C_{H_2O, CO_2} = \frac{A \times M}{d \times \rho \times \epsilon} \quad (1)$$

where C is the concentration of H₂O or CO₂ (in wt%), A the absorbance

measured on the spectral band of the water or CO₂, M the molar mass of the molecule (in g.mol⁻¹), d the thickness of the object (i.e. the melt inclusion) passed through (in cm), ρ its density (in g/l) and ε the absorption coefficient or absorptivity which depends on the nature of the glass (in l/mol.cm). Details of the parameters used for each melt inclusion are given in Supplementary Material A, Tables A.2 and A.3.

The associated final error (obtained by error propagation) is less than 0.13 wt% for H₂O and 100 ppm for CO₂. Two melt inclusions were analyzed for H₂O content by Raman and FTIR spectroscopies: the difference between the contents obtained from the two methods is less than 5% for one and about 25% for the other.

3.2.4. Electron microprobe (EPMA)

After being analyzed by Raman spectroscopy, and for some by FTIR spectroscopy, the melt inclusions, in addition to the few groundmasses and the embayment, were analyzed with the Cameca SX Five electron microprobe at LMV to determine the concentrations of major and volatile elements (S, Cl with F being systematically under the detection limit of around 600 ppm). Two analysis procedures were used. In both cases a voltage of 15 kV was used and the beam size varied between 10 and 20 μm. For the analysis of major elements, the current is 4 or 8 nA, while for the analysis of volatile elements it is 40 nA. The associated average errors (2σ) are 0.67 wt% for SiO₂, 0.06 wt% for TiO₂, 0.21 wt% for Al₂O₃, 0.28 wt% for FeO, 0.08 wt% for MnO, 0.14 wt% for MgO, 0.17 wt% for CaO, 0.13 wt% for Na₂O, 0.05 wt% for K₂O, 0.06 wt% for P₂O₅, 105 ppm for S and 100 ppm for Cl.

Two additional procedures were used for the analysis of major elements in host crystals containing melt inclusions and in clinopyroxenes intended for barometric estimates. These were also carried out at a voltage of 15 kV but with a current of 15 nA and a focused beam. The difference between these two procedures is the counting time for the different elements, which is increased for clinopyroxene crystals to minimize the uncertainty in the measurement and therefore in the barometric estimates (Supplementary Material A). The average errors (2σ) associated with the host crystal procedure are 0.50 wt% for SiO₂, 0.06 wt% for TiO₂, 0.07 wt% for Al₂O₃, 0.22 wt% for Cr₂O₃, 0.27 wt% for FeO, 0.10 wt% for MnO, 0.33 wt% for MgO, 0.06 wt% for CaO, 0.05 wt% for Na₂O and 0.02 wt% for K₂O. Those associated with the special clinopyroxene procedure are 0.30 wt% for SiO₂, 0.02 wt% for TiO₂, 0.07 wt% for Al₂O₃, 0.04 wt% for Cr₂O₃, 0.11 wt% for FeO, 0.06 wt% for MnO, 0.13 wt% for MgO and CaO and 0.02 wt% for Na₂O.

3.2.5. Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS)

Trace elements in melt inclusions of a suitable size (< 30 μm) were also measured in situ using the Resonetics M50 EXCIMER Laser (wavelength 193 nm) coupled to the Agilent 8900 ICP-MS at LMV. Data was then processed using Glitter software and the CaO content previously measured by electron microprobe as the internal standard. Two external standards were also analyzed at the beginning, middle and end of the sequence, one with a basaltic composition and the other with a dacitic composition (Supplementary Material B, Table B.2). Because of the high variability of the analytical precision (6–46% relative error, cf. Supplementary Material B, Table B.2), all trace element data are presented in the Results section but only data with relative errors of less than 15% are kept for the Discussion section.

3.2.6. MultiGAS

The gases from the Mombacho fumaroles were analyzed in situ during the 2024 field campaign (February 22nd) using a MultiGAS instrument from the INGV – Sezione di Palermo. The MultiGAS consists of a Gascard IR spectrometer for CO₂ measurements. The spectrometer is calibrated over the 0–3000 ppmv range, with an accuracy of 2% and a resolution of 0.8 ppmv. Two electrochemical sensors are also used to measure SO₂ and H₂S. For SO₂, the sensor is a 3ST/F type calibrated over the 0–200 ppmv range. It has an accuracy of 2% and a resolution of 0.5

ppmv. For H_2S , the sensor is type 2E and is calibrated over the 0–200 ppmv range. It has an accuracy of 5% and a resolution of 0.25 ppmv. A relative humidity (RH) sensor is used to measure H_2O , and atmospheric pressure is recorded by a sensor on the CO_2 spectrometer. All the sensors are connected to a Campbell Scientific CR6 data logger for capturing, acquiring and recording data at 1 Hz and have been calibrated in the laboratory with gases of known composition.

Once the instrument was warmed up in the field, it was positioned at a short distance (< 20 m) from the fumarole source vent at 0.5–1 m height above the ground (to minimize any influence from accumulation at the soil-air interface). Then, for each measurement, the MultiGAS was kept in the acquisition position for around ten minutes and a GPS point was taken. A total of 15 measurements were taken in the crater fumarolic field.

The gas molar ratios obtained were derived from a linear regression (using the least squares method) of the composition of each component as a function of H_2S , which is a purely volcanic species, using the software RatioCalc (Tamburello, 2015). Only the ratios obtained with a regression coefficient $R^2 > 0.6$ were considered. Moreover, due to the low SO_2 content of the Mombacho gases, $\text{SO}_2/\text{H}_2\text{S}$ ratios were only calculated when the average SO_2 concentration was higher than the resolution of the sensor, i.e. 0.5 ppmv. The $\text{CO}_2/\text{H}_2\text{S}$ ratios are corrected for the effect of pressure.

4. Results

4.1. Petrographic description of the samples

Samples MBQ1, MBQ2B, MBQ2L2 and MBT2 are millimeter to centimeter-sized black vesiculated lapilli. They contain olivine and clinopyroxene crystals and a few rarer plagioclase crystals. The largest crystals (100–1000 μm) are euhedral to subhedral (Supplementary Material A, Fig. A.1a, b). Some pyroxene crystals show complex inverse or oscillatory zoning (Fig. 2a) and/or core resorption textures. Pyroxene and plagioclase crystals are also present as microliths in the groundmass. Sample MBT1 consists of centimetric vesiculated beige pumices. They contain orthopyroxene and plagioclase crystals and a few rarer plagioclase phenocrysts. The largest crystals and phenocrysts (100–1500 μm) are also euhedral to subhedral, and some are agglomerated (Supplementary Material A, Fig. A.1b).

The investigated melt inclusions are glassy and contain no secondary minerals, with only a few containing a sulfide globule (Supplementary Material A, Fig. A.1c, d, e, f). The olivine-hosted melt inclusions are round or oval, some are negatively shaped, and are randomly distributed in the mineral (Supplementary Material A, Fig. A.1c, f). They measure between 50 and 200 μm and most have a shrinkage bubble. Those hosted by clino- and orthopyroxene crystals are mostly oval, but some have more complex shapes (Supplementary Material A, Fig. A.1d). They are

also smaller, measuring between 25 and 100 μm . In sample MBQ2L2, almost all have a shrinkage bubble. On the other hand, in sample MBT2 there are almost as many with or without a bubble, and in sample MBT1, almost none of them have a shrinkage bubble. The plagioclase-hosted melt inclusions are ovoid or even rectangular in shape and rarely measure more than 70 μm (Supplementary Material A, Fig. A.1e). There are two populations of inclusions, one containing a shrinkage bubble and the other not.

Groundmasses of samples MBQ1, MBQ2B, MBQ2L2 and MBT2 are crystallized or micro-crystallized. Only the groundmass of sample MBT1 is relatively well quenched. The groundmass of MBQ1 is dark brown and completely micro-crystallized. Groundmasses of MBQ2B, MBQ2L2 and MBT2 are similar and present two different textures. A yellowish-brown crystallized groundmass and a grey-brown micro-crystallized groundmass are in contact (Fig. 2b). In places the contact is sharp, in others it is more diffuse and gradual.

4.2. Whole rock (WR) and groundmass chemistry

Databases related to whole rock and groundmass chemistry are available in Supplementary Material B, Tables B.1 and B.3 respectively. Whole rock SiO_2 contents of the eleven samples from this study range from 46.2 to 64.1 wt% while the major alkaline element contents ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) range from 1.4 to 6.8 wt% (Fig. 3). The Mombacho eruptive products extend from basalts to dacites and are aligned along the calc-alkaline series. Most of the major oxides (TiO_2 , FeO , MnO , MgO and CaO) correlate negatively with silica, while the alkalis correlate positively. Among these eleven samples, three groups can be distinguished (Fig. 3). The first group (Gr. 1) comprises the basaltic samples with the lowest silica and alkali contents, including MBQ1, MBQ2B and MBQ2L2 (46.2–47.5 wt% SiO_2 ; 1.4–2.3 wt% $\text{Na}_2\text{O} + \text{K}_2\text{O}$). The second group (Gr. 2) is made up of the basaltic samples richest in silica and alkalis, including MBT2 (49.9–50.8 wt% SiO_2 ; 2.6–3.6 wt% $\text{Na}_2\text{O} + \text{K}_2\text{O}$). And the third group (Gr. 3) is composed of samples with more evolved composition ranging from andesites to dacites, including MBT1 (58.5–64.1 wt% SiO_2 ; 5.1 to 6.8 wt% $\text{Na}_2\text{O} + \text{K}_2\text{O}$).

The presence of an embayment within one of the olivine crystals of MBQ2L2 (Gr.1) allowed to overcome the fact that groundmasses of all the Gr. 1 samples are crystallized. The embayment of MBQ2L2 (Gr. 1) is basaltic, like the rock from which it is derived, but it is richer in silica and alkalis (Fig. 3). It contains an average of 47.9 wt% SiO_2 and 2.5 wt% $\text{Na}_2\text{O} + \text{K}_2\text{O}$, as well as 10.8 wt% FeO and 6.7 wt% MgO . For sample MBT2 (Gr. 2), which also has crystallized groundmass, no embayment was found. Several measurements were therefore taken in different zones, as free as possible of microcrystals, in order to obtain an average composition. MBT2 groundmass is composed of an average of 56.2 wt% SiO_2 , 4.0 wt% $\text{Na}_2\text{O} + \text{K}_2\text{O}$, 10.7 wt% FeO and 3.4 wt% MgO . As for the MBQ2L2 embayment, it is more differentiated than its host rock and lies

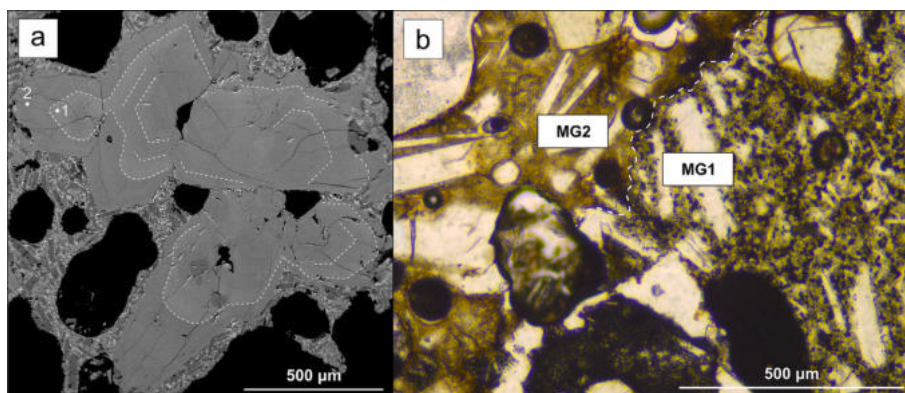


Fig. 2. a. Back Scattered Electron (BSE) image of a zoned clinopyroxene from sample MBQ1. The Mg# at point 1 is 79 and at point 2 is 84. b. Polarized analyzed light photograph of sample MBQ2B where two different groundmasses (MG) are visible and in contact, separated by the dotted lines.

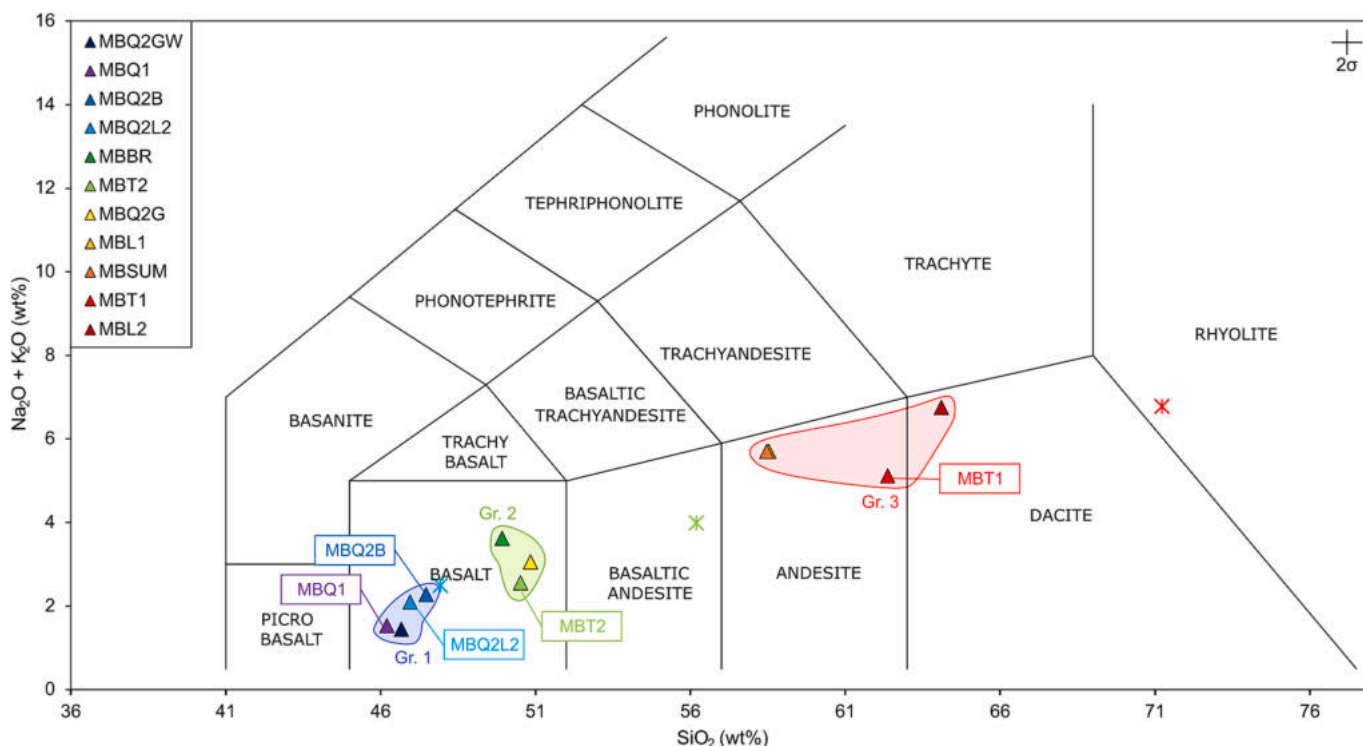


Fig. 3. Whole rock compositions of the eleven sample of this study, Group 1 (MBQ2BGW, MBQ1, MBQ2B, MBQ2L2), Group 2 (MBBR, MBQ2G, MBT2) and Group 3 (MBL1, MBSUM, MBL2, MBT1). Labelled samples are those on which petrological investigations focus, and crosses are groundmass compositions.

in the field of basaltic andesites (Fig. 3). The groundmass from MBT1 (Gr. 3), unlike the others, is not visibly crystallized. Nevertheless, several analyses were also carried out at different points in order to have an average composition. The groundmass is rhyolitic in composition and contains on average 71.2 wt% SiO₂, 6.8 wt% Na₂O + K₂O as well as 1.9 wt% FeO and 0.3 wt% MgO (Fig. 3).

4.3. Mineralogy

Databases related to minerals and clinopyroxene crystals compositions are available in Supplementary Material B, Tables B.4 and B.5. The melt inclusions of this study are hosted in olivine, pyroxene and plagioclase crystals distributed in the five samples chose for petrological investigations (MBQ1, MBQ2B, MBQ2L2, MBT2 and MBT1). The olivine crystals can be divided into two populations (Fig. 4a). The first includes olivine crystals from Gr. 1 (MBQ1, MBQ2B and MBQ2L2), which have forsterite (Mg#) contents between 80 and 87. The second population comprises olivine crystals from Gr. 2 (MBT2), which have lower

forsterite contents between 70 and 72. No olivine crystals were found in Gr. 3 (MBT1). Two populations of pyroxene crystals can also be distinguished (Fig. 4b). The first includes crystals from Gr. 2 (MBT2), which have enstatite (En_x) contents between 42 and 44. These are clinopyroxene crystals, half of which are augites and the other half diopsides. The second population consists of crystals from Gr. 3 (MBT1) which are orthopyroxenes and have higher enstatite contents, between 59 and 64. Finally, the plagioclase crystals in this study from Gr. 2 (MBT2) and Gr. 3 (MBT1) are significantly different. The plagioclase crystal from Gr. 2 (MBT2) is an anorthite with An_x content of 84. The crystals in Gr. 3 have anorthite contents of 44 and 49 respectively and are bytownites.

4.4. Geochemistry of melt inclusions (MIs)

4.4.1. Post-entrapment modifications

The composition of melt inclusions hosted in olivine crystals were corrected for post-entrapment crystallisation (PEC) using the MIMiC software (Rasmussen et al., 2020). The equilibrium constant K_D

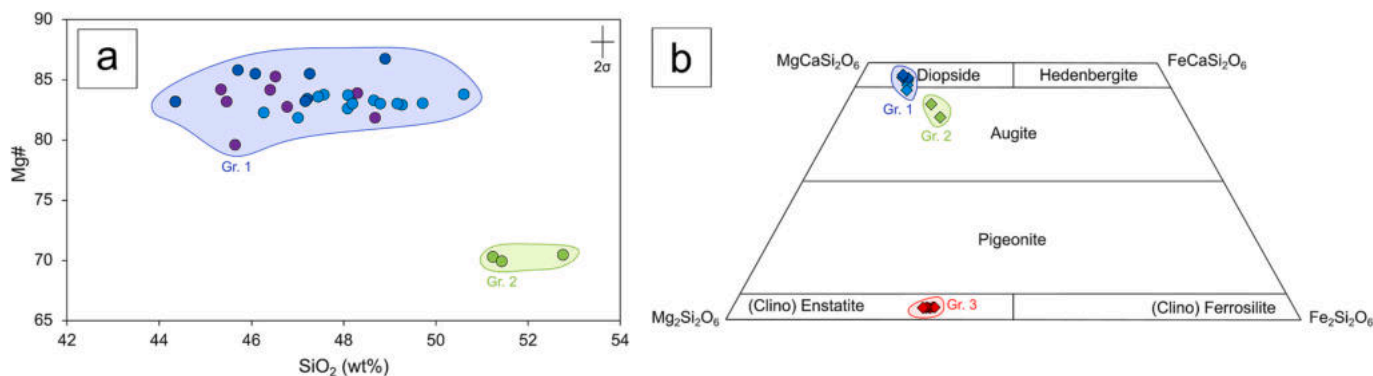


Fig. 4. a. Mg# of olivine crystals as a function of the SiO₂ content of the corresponding melt inclusions. b. Enstatite content of pyroxene crystals. Colour code for the distinct samples is the same that in Fig. 3.

(Fe—Mg) calculated following Toplis (Toplis, 2005) was used to calculate the equilibrium between the host crystal and the melt inclusion. The relative proportions of Fe_2O_3 and FeO in the melt inclusions of this study, necessary for the correction, were not directly measured. For each inclusion, the corresponding relative proportions of Fe_2O_3 and FeO were calculated using the method of Kress and Carmichael (Kress and Carmichael, 1991) based on melt composition, crystallisation pressure and temperature, and oxygen fugacity. As oxygen fugacities were not directly measured in this study either, they were also calculated using the method of Kress and Carmichael (Kress and Carmichael, 1991). For this, we used five whole rock data from Mombacho where Fe_2O_3 and FeO have been directly measured (McBirney and Williams, 1965). By comparison of the measured K_D with the theoretical one to reach equilibrium, MIMiC results indicate that approximately 80% of the melt inclusions show between 0.5 and 9.8% (2.1% on average) of post-entrapment crystallisation of the host crystal at the rim of MIs. Correction for iron loss (Fe-Loss, (Rasmussen et al., 2020; Danyushevsky et al., 2000)) was not carried out, as the melt inclusions were not significantly depleted in iron compared with the whole rocks.

Since corrections are less constrained or not possible for melt inclusions hosted by pyroxene and plagioclase crystals because chemical diffusion processes in these minerals are less studied and understood, only those with K_D at equilibrium were retained in the database of major and volatile element compositions. For a plagioclase in equilibrium with its liquid, the K_D (Na—Ca) must be equal to 0.10 ± 0.05 for a magma at a temperature below 1050 °C and 0.28 ± 0.11 for a magma at a higher temperature (Putirka, 2008). The K_D (Fe—Mg) should be equal to 0.27 ± 0.03 for clinopyroxene crystals in equilibrium with their liquid and 0.29 ± 0.06 for orthopyroxene crystals (Putirka, 2008).

Finally, 52 melt inclusions out of 78 were retained: 31 inclusions in

olivine crystals corrected by MIMiC, and 21 inclusions in pyroxene and plagioclase crystals for which the conditions of equilibrium with the host crystal were achieved.

4.4.2. Major element compositions

Major element compositions of melt inclusions are available in Supplementary Material B, Table B.6. In a similar manner as for the whole rocks, the melt inclusions cover a wide range of compositions and align with the calc-alkaline series (Fig. 5) from basaltic (44.3 wt% SiO_2) to rhyolitic compositions (73.7 wt% SiO_2). For samples MBQ1 and MBQ2B, the composition of around half of the melt inclusions is more differentiated (SiO_2 and $\text{Na}_2\text{O} + \text{K}_2\text{O}$ enrichment) than the corresponding whole rock. For samples MBQ2L2, MBT2 and MBT1, most of the melt inclusions have higher SiO_2 and $\text{Na}_2\text{O} + \text{K}_2\text{O}$ contents than the corresponding whole rock.

The melt inclusions form the same three groups as for the whole rocks (Fig. 5). Those from Gr. 1 (MBQ1, MBQ2B and MBQ2L2) trapped basaltic liquids (44.3–50.6 wt% SiO_2). Those from Gr. 2 (MBT2) trapped basaltic and andesitic melts (48.7–59.1 wt% SiO_2) and those from Gr. 3 have dacitic and rhyolitic compositions (69.3–73.7 wt% SiO_2). The major oxides FeO, MgO, Al_2O_3 and CaO show a negative correlation with SiO_2 , while Na_2O and K_2O increase with SiO_2 (Fig. 5; Supplementary Material A, Fig. A.2). TiO_2 , on the other hand, seems to show a more complex evolution, with a wide range of values within Gr. 1 (0.62–1.50 wt%) and then a clear decrease in content between Gr. 2 and Gr. 3 (Fig. 5).

4.4.3. Volatile element compositions

Volatile element compositions of melt inclusions are available in Supplementary Material B, Table B.6. H_2O , S and Cl contents are plotted

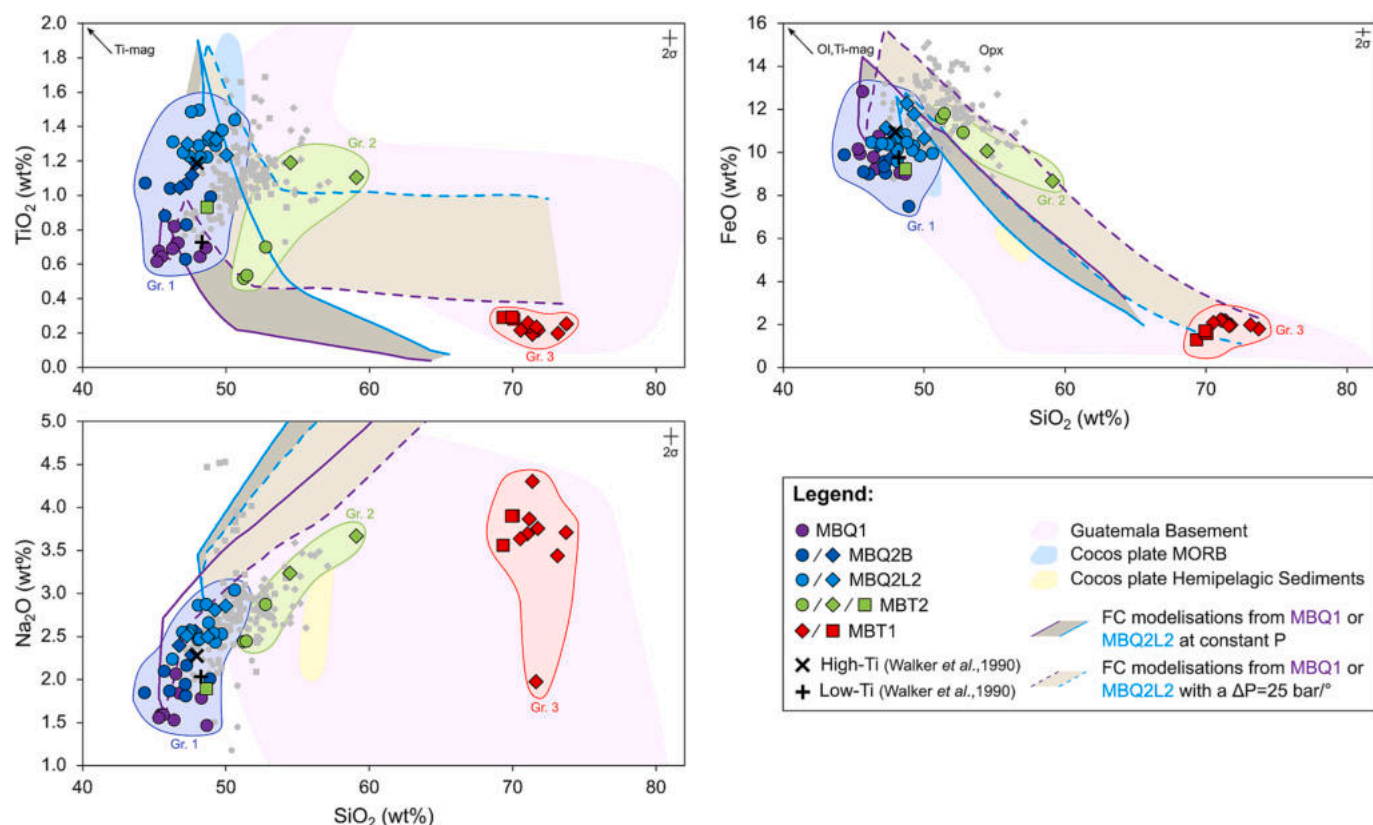


Fig. 5. Melt inclusions major elements data corrected for post-entrapment crystallisation. Four fractional crystallisation models are shown. Two (light blue) start from the Ti-richest MI of Gr. 1 (MBQ2L2), two others (purple) start from the poorest one (MBQ2B). Circles are olivine-hosted MIs, diamonds are pyroxene-hosted MIs and squares are plagioclase-hosted MIs. Grey symbols are MIs data from the Masaya (Zurek et al., 2019) and Cerro Negro (Venugopal et al., 2016). The data used to define the continental crust, sedimentary and MORB fields from Heydolph et al. (Heydolph et al., 2012) and Patino et al. (Patino et al., 2000). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

as a function of K_2O which is a good marker of differentiation in the case of calc-alkaline magmas because of its high incompatibility (Fig. 6a). The liquids trapped in the melt inclusions cover a wide range of H_2O contents, from less than 1000 ppm (below the detection limit) to nearly 6.0 wt% (Fig. 6a). For the Gr. 1, H_2O content dissolved in melt inclusions varies widely from 0.5 to 4.1 wt%. In Gr. 2, melt inclusions display H_2O content ranging from 1.2 to 2.4 wt%. In Gr. 3, the most differentiated, melt inclusions have the highest H_2O contents, up to 6.0 wt% together with the highest K_2O contents. Embayment and groundmasses contain on average less H_2O than associated melt inclusions (0.9 wt% H_2O for the Gr.1 embayment and 4.0 wt% H_2O for the Gr. 3 groundmass; in Gr. 2 the groundmass H_2O content was not quantified).

Of the twelve melt inclusions analyzed for H_2O and CO_2 content by FTIR spectroscopy, six are removed from the H_2O database considered for this study, and five for the CO_2 (cf. Supplementary Material A). The H_2O contents of the melt inclusions in Gr. 1 measured by FTIR spectroscopy ranged from 0.9 to 1.9 wt% and agree with the data obtained by Raman spectroscopy (Table 1). As the error associated with FTIR spectroscopy (0.13 wt%) is smaller than the one associated with Raman spectroscopy (0.2 wt%), the FTIR H_2O values are considered when both are present. Looking at Raman and FTIR data, there is no significant difference of H_2O content between melt inclusions containing a bubble (average 1.5 ± 0.13 wt%) and those without (average 1.3 ± 0.13 wt%). The glass CO_2 content of bubble-free melt inclusions in Gr. 1 varies from 802 to 1071 ppm, whereas that of the melt inclusion containing a bubble is 438 ppm. In light of this difference, a 3D Raman tomography of the bubble was performed to quantify the CO_2 content stored in the bubble in the form of fluid and carbonates and finally determine the total CO_2 content of the melt inclusion (results detailed below). The melt inclusion in Gr. 3 does not appear to contain any detectable dissolved CO_2 or carbonates (Table 1).

In terms of dissolved S content, the melt inclusions in Gr. 1 also show a large variability, with content ranging from 376 to 2089 ppm independently of the K_2O content (Fig. 6b). On the other hand, the melt inclusions in Gr. 2 and 3 show a clear decrease in S content from 1183 ppm to concentrations below the detection limit, correlated with an increase in K_2O content (Fig. 6b). The average S content of the embayment in Gr. 1 (986 ppm) is similar to that of the melt inclusions from the same group. Groundmasses in Gr. 2 and 3 are poorer in S (178 and 99 ppm, respectively) compared to the melt inclusions of the same groups.

Chlorine shows a positive correlation with K_2O (Fig. 6c). From the most mafic to the most differentiated liquids, the Cl concentration ranges from 314 to 2677 ppm. A plateau appears to have been reached for melt inclusions in Gr. 3. The Cl contents of the embayment and groundmasses follow the same path than that of the melt inclusions, showing an enrichment with the increasing SiO_2 content.

Finally, the qualitative Raman spectroscopy analysis of the bubbles in the melt inclusions show that carbonates and a few sulfides are present in the majority of the bubbles in the melt inclusions of Gr. 1. On the other hand, only a few rare sulfides and sulfates, but no carbonates, are present in the analyzed bubbles in the melt inclusions of Gr. 2 and no sulfides in those of Gr. 3. The 3D Raman tomography of the bubble of MBQ2L2 Ol6 MI9 melt inclusion (Gr.1) revealed the presence of two types of minerals which cover bubble walls: carbonates and sulfides. Fluid CO_2 is also present. A semi-quantitative estimate of the volume of carbonate crystals and fluid CO_2 in the bubble gives a total CO_2 content of the melt inclusion (glass + bubble) of 7000 ± 1100 ppm. As the CO_2 content of the glass is 438 ppm, more than 94% of the budget is sequestered in the bubble of the melt inclusion. If we consider the sulfide crystals, the sulfur content of the melt inclusion (glass + bubble) is 1580 ± 40 ppm. As the S content of the glass is 1232 ppm, 22% of the sulfur budget is sequestered in the melt inclusion bubble.

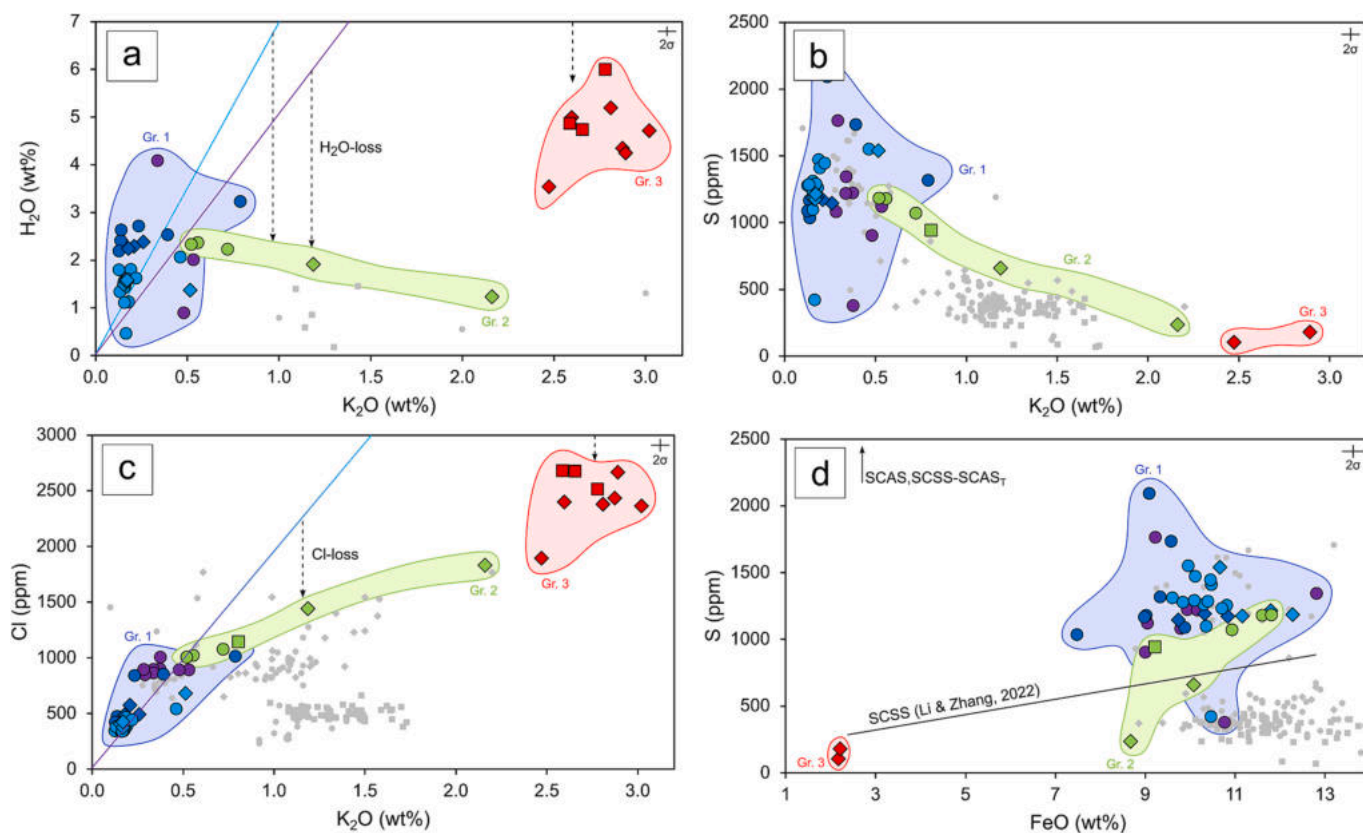


Fig. 6. Volatile contents relative to K_2O contents of melt inclusions (a. H_2O , b. S, c. Cl). d. FeO vs. S. Data is corrected for post-entrapment crystallisation. Dotted lines represent the theoretical loss in volatile elements by degassing. In the FeO vs. S graph, the sulfur concentration at sulfide saturation is also plotted. Grey symbols are MIs data from the Masaya (Zurek et al., 2019) and Cerro Negro (Venugopal et al., 2016).

Table 1H₂O and CO₂ concentrations in glass (gl.) and glass + bubble (tot.) acquired by FTIR spectroscopy and comparison with Raman data.

Sample	MI	H ₂ O FTIR gl. (± 0.1 wt%)	H ₂ O Raman gl. (± 0.2 wt%)	CO ₂ FTIR gl. (± 100 ppm)	Bubble	CO ₂ Raman tot. (± 1100 ppm)	H ₂ O Raman gl. sample average
MBQ1 (Gr. 1)	Ol4 MI4	1.9	/	/	Yes	/	4.1 ($n = 1$)
	Ol5 MI5	0.9	/	802	No	/	
	Ol3 MI4	1.8	/	1051	No	/	
MBQ2L2 (Gr. 1)	Ol6 MI9	1.1	1.5	438	Yes	7000	1.6 ($n = 12$)
	Ol10 MI14	1.4	1.5	1032	No	/	
	Ol10						
	MI14.1	1.3	/	897	No	/	
MBT1 (Gr. 3)	Px15 MI15	/	/	n.d	No	/	4.7 ($n = 9$)

4.4.4. Trace element compositions

Trace element compositions of melt inclusions are available in Supplementary Material B, Table B.2. Trace element compositions show a typical arc magma pattern with a marked enrichment in large ion lithophile elements (LILE like Ba, Rb, Sr) and with lower concentrations in high field strength elements (HFSE like Nb, Ta, Th) for all the melt inclusions (Fig. 7). Values are normalized to the primitive mantle (McDonough and Sun, 1995). Although all the melt inclusions from a same sample generally follow the same pattern, there is significant variability between samples. For instance, there is a clear divergence within the Gr. 1, between samples MBQ1, MBQ2B and MBQ2L2, especially in LILE (see Ba, Rb, Sr) and HFSE (see Nb, Ta, Zr, Hf), with the HFSE/LILE ratios being lower in sample MBQ1 and higher in samples MBQ2B and MBQ2L2. Another chemical disparity exists also between the most mafic (Gr. 1) and the most differentiated (Gr. 3) melt inclusions. The latter are more enriched in most LILE, HFSE and LREEs but relatively depleted in HREEs, Eu and Sr. As for major elements, the composition of the melt inclusions in Gr. 2 is intermediate between those of Gr. 1 and 3, except for MREEs and HREEs with the highest contents in our dataset.

4.5. Gas chemistry

The gases from the Mombacho fumaroles were sampled in the diluted plume near the vents in the crater (Fig. 8). In general, they have low SO₂ content (< 4 ppmv) and are mainly composed of H₂S, CO₂ and H₂O. H₂O/H₂S molar ratios range from 100 to 415, CO₂/H₂S from 2.8 to 20.0 and the SO₂/H₂S molar ratio range from 0 to 0.26 due to the small amount of SO₂ (Table 2). One of the ratios of gaseous species classically used to study volcanic gases, in particular degassing paths, is the CO₂/S_T ratio where S_T represents the total sulfur molarity brought by H₂S and SO₂. When the quantity of SO₂ is below the detection limit, this ratio is directly equal to CO₂/H₂S. The CO₂/S_T ratios obtained in the fumarolic zone of the crater range from 2.8 to 19.9 in this study, which is in the same order of magnitude as those, ranging from 2.7 to 49.4, obtained by Garofalo et al. (Garofalo et al., 2007).

5. Discussion

5.1. Magma storage conditions

By combining the H₂O and CO₂ contents of the melt inclusions, it is possible to derive an entrapment pressure using saturation models (Ghiorso and Gualda, 2015; Allison et al., 2019; Papale et al., 2006). In

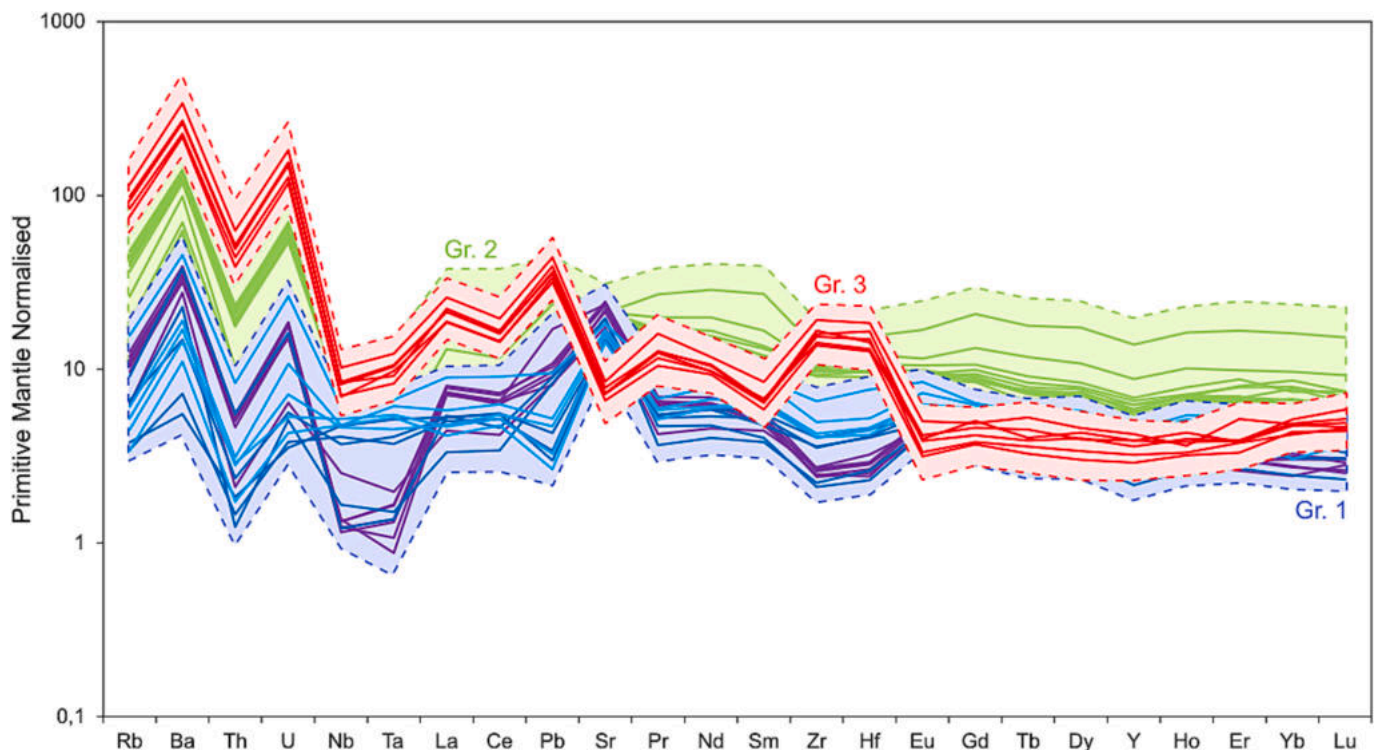


Fig. 7. Primitive-mantle normalized (McDonough and Sun, 1995) trace elements for Mombacho melt inclusions.



Fig. 8. Location of MultiGAS measurement points, numbers correspond to those presented in Table 2. The symbol on the map represents the point of view from which the photograph was taken.

Table 2
Mombacho crater fumarole gas composition from MultiGAS measurements. Ratios in *italics* are those for which only H₂S is considered in the S_T because the SO₂ content is below the detection limit.

Pt.	H ₂ O/H ₂ S	R ²	CO ₂ /H ₂ S	R ²	SO ₂ /H ₂ S	R ²	CO ₂ /S _T
1	295	0.83	7.95	0.92	n.d	/	7.9
2	173	0.96	4.60	0.97	n.d	/	4.6
3	219	0.97	5.30	0.98	n.d	/	5.3
4	200	0.96	4.79	0.94	n.d	/	4.8
5	258	0.97	7.16	0.92	n.d	/	7.2
6	102	0.83	4.18	0.94	0.025	0.90	4.1
7	148	0.98	3.52	0.95	0.004	0.88	3.5
8	125	0.85	2.82	0.82	n.d	/	2.8
9	148	0.97	4.32	0.96	0.032	0.90	4.2
10	164	0.87	6.52	0.90	0.093	0.80	6.0
11*	241	0.86	9.61	0.90	0.260	0.84	7.6
12	134	0.93	4.55	0.97	0.016	0.63	4.5
13	413	0.73	19.95	0.93	n.d	/	19.9
14	219	0.87	8.20	0.91	n.d	/	8.2
15	142	0.80	5.80	0.93	0.041	0.75	5.6

* Sulfur pool.

this study the model MagmaSat of Ghiorso and Gualda (Ghiorso and Gualda, 2015) is used to calculate these pressures. It is a mixed H₂O-CO₂ fluid saturation model, well adapted and calibrated for calc-alkaline magmas (Allison et al., 2019). The pressures obtained for the different olivine-hosted melt inclusions in Gr. 1 are 200 ± 60 MPa for MBQ1 and 190 ± 40 MPa for MBQ2L2 (Table 3). As the melt inclusions in Gr. 3 contain undetectable amounts of CO₂, mixed fluid saturation pressures could not be calculated but it H₂O saturation pressures have been calculated. Using the model MagmaSat of Ghiorso and Gualda (Ghiorso and Gualda, 2015), the Gr. 3 pressures cover a wide range from 80 to 190 ± 10 MPa (Table 3). Whether the melt inclusions are hosted by orthopyroxene or plagioclase crystals, the pressures obtained are within the same range. As water could not be observed in the bubbles of the studied melt inclusions, we assume that saturation pressures based on the H₂O content of the glass alone are not underestimated. However, 3D Raman tomography of the bubble of a melt inclusion in Gr. 1 (MBQ2L2 Ol6 MI9) revealed that a large proportion of the CO₂ was stored in the bubble and not in the glass, either in the form of carbonates and fluid CO₂ (94%). It is therefore necessary to consider the CO₂ content of the bubble of a melt inclusion, when it has one, in the solubility pressure calculations. Therefore, the new saturation pressure obtained by considering the carbonates and fluid CO₂ in the bubble of the melt inclusion in Gr. 1 is 850 ± 180 MPa. This saturation pressure is much higher than those given by the melt inclusions in the same group that do not contain bubble. Thus, by looking at the saturation pressure of inclusions with a bubble and considering the quantity of volatile elements contained in it, we have access to a deeper, less degassed part of the system. Due to the volume ratio of the bubble to the melt inclusions,

Table 3
Barometric and thermometric estimates based on the clinopyroxene crystals composition and the solubility of H₂O and CO₂. All pressures are in MPa. Errors of clinopyroxene-based barometric estimates are the standard errors of estimate (SEE) of the equations (Putirka, 2008; De Moor et al., 2013). Errors of the H₂O-CO₂ solubility-based barometric estimates represent a combined mixture and propagated errors from the solubility models used in this study and analytical errors.

Sample	Clinopyroxene crystals composition				Volatile elements solubility		
	P _{32a} (± 310)	P _{32b} (± 260)	P _{Wang} (±170)	T _{Wang} (± 37 °C)	MI	H ₂ O- CO ₂ (± 50)	H ₂ O (± 10)
MBQ1 (Gr.1)	320	290	210	1107	Ol5	200	/
MBQ2B (Gr. 1)	430	390	190	1091	MI5	/	/
					Ol3	/	/
					MI4	210	/
						850	/
					Ol6	(±	/
					MI9	180)	/
					Ol10	/	/
					MI14	200	/
MBQ2L2 (Gr. 1)	250	410	260	1138	Ol10	/	/
MBT2 (Gr. 2)	340	430	140	1077	MI14.1	280	/
						/	/
					Px3	/	/
					MI3	/	110
					Px4	/	/
					MI4	/	80
					Px8	/	/
					MI6	/	110
					Px10	/	/
					MI8	/	150
					Px11	/	/
					MI11	/	140
					Px12	/	/
					MI12	/	130
					PI7 MI1	/	190
MBT1 (Gr. 3)	/	/	/	/	PI8 MI2	/	130
					PI8 MI3	/	140

which is 3%, the hypothesis of heterogeneous trapping of the melt inclusion hypothesis can be set aside. Melt inclusions without bubbles, in contrast, give us information about the more superficial part of the storage, which is already more degassed.

The chemistry of the clinopyroxene crystals analyzed in MBQ1, MBQ2B, MBQ2L2 and MBT2 thin sections for barometric estimates (see Supplementary Material A for the protocol) is consistent and representative of the host crystals of melt inclusions (Supplementary Material B, Tables B.4 and B.5). Some show complex inverse or oscillatory zoning

(Fig. 2a). Evidence of core resorption textures was also observed. No clinopyroxene crystal were found in sample MBT1. In this study, three geobarometers based on the composition of clinopyroxene crystals were tested: Eqs. (32a) and (32b) of Putirka (Putirka, 2008) and the equation of Wang et al. (Wang et al., 2021). Eq. (32b) by Putirka (Putirka, 2008) also considers the H₂O content of the sample. An average H₂O content per sample was calculated based on the analysis made in the melt inclusions by Raman and FTIR spectroscopy. Due to the smaller standard error of estimate (SEE) and the better agreement with the pressures based on the H₂O-CO₂ solubility, the results from the barometer of Wang et al. (Wang et al., 2021) are presented in the following part of this study. For Gr. 1, the H₂O-CO₂ solubility gives an average crystallisation pressure of 200 ± 50 MPa, which is identical to the average pressure of 220 ± 170 MPa given by the barometer of Wang et al. (Wang et al., 2021). The clinopyroxene crystals of Gr. 2 (140 ± 170 MPa) show slightly lower crystallisation pressures than those of Gr. 1 (220 ± 170 MPa on average) (Table 3). This difference is however within in the barometer uncertainty (SEE).

In summary, the compositions of clinopyroxene crystals in Gr. 1 and 2 indicate a main storage zone between 220 ± 170 MPa, i.e. 8.6 ± 6.7 km assuming a crustal density of 2600 kg/m^3 (Zurek et al., 2019), and 140 ± 170 MPa (Gr. 2), i.e. 5.5 ± 6.7 km. As the difference in pressure is within the analytical uncertainty (40 MPa) of the barometer, it would appear to be a single zone within which the magmas can differentiate. Even though barometry based on H₂O-CO₂ solubility could give minimum values, its higher accuracy allows to better define this zone at 200 ± 50 MPa (Gr. 1), i.e. 8.2 ± 1.6 km. The wide range of H₂O solubility-derived storage pressures of Gr. 3 ($80\text{--}190 \pm 10$ MPa, i.e. $3.1\text{--}7.4 \pm 0.4$ km) is in the range of Gr. 1 and Gr. 2 pressures estimated by the composition of clinopyroxene crystals considering the associated errors. However, H₂O solubility-derived storage pressures of Gr. 3 seem converge towards shallower levels (on average 130 ± 10 MPa, i.e. 5.1 ± 0.4 km) than those from the other groups.

A thermometer was used in conjunction with the barometer developed by Wang et al. (Wang et al., 2021). It gives an average temperature of 1112 ± 37 °C for Gr. 1 and temperatures of 1077 and 987 ± 37 °C for Gr. 2 and 3, respectively (Table 3). These pressures and temperatures, obtained using thermobarometry on clinopyroxene crystals, were used to define the oxygen fugacity conditions for the different magmas. As explain previously, oxygen fugacities were calculated (Kress and Carmichael, 1991) based on Mombacho whole rock data previously acquired by McBirney and Williams (McBirney and Williams, 1965), for which the respective quantities of Fe₂O₃ and FeO were measured. Relative to the FMQ buffer, the oxygen fugacities are +2.3, +1.9, +2.1, +3.0 and +4.6 log units higher for magmas respectively at 47.9, 51.1, 53.7, 58.0 and 66.7 wt% SiO₂. The SiO₂ contents correspond to the silica contents of the whole rock data of McBirney and Williams (McBirney and Williams, 1965). As these oxygen fugacities are not calculated directly from the samples in this study (see Section 4.4.1 Post-entrapment modifications), they should be used with caution.

The storage conditions (pressure, temperature, oxygen fugacity) at Mombacho calculated here are of the same order of magnitude as those of other edifices in the same volcanic chain. The depth of magma storage, estimated here between 8.2 ± 1.6 km and 3.1 ± 0.4 km, is in line with the storage depths assumed for Masaya, which are 11.5 and 4.5 km (Zurek et al., 2019), and for Cerro Negro, which is around 7 km (Venugopal et al., 2016). The basaltic magmas at Mombacho have an average temperature of 1112 ± 37 °C similar to the ones reported at Masaya ($1097\text{--}1127$ °C; (De Moor et al., 2013)), Cerro Negro ($1017\text{--}1174$ °C; (Venugopal et al., 2016)) and Momotombo ($1070\text{--}1110$ °C; (Tramontano et al., 2025)). Finally, the oxygen fugacities of basaltic magmas we estimated at Mombacho ($\text{FMQ} + 2.3 \pm 0.6$) agree with the oxidizing conditions reported for basaltic magmas at Masaya ($\text{FMQ} + 1.7 \pm 0.4$; (Zurek et al., 2019)), Cerro Negro ($\text{FMQ} + 2.0 \pm 0.3$; (Venugopal et al., 2016)) and Momotombo ($\text{FMQ} + 1.1\text{--}1.9$; (Tramontano et al., 2025)).

5.2. Magmatic processes

As shown by the major and trace element compositions of the melt inclusions (Figs. 5 and 7), two types of variability can be observed. Firstly, there is variability between the three groups, both in terms of major and trace elements. Secondly, there is variability within Gr. 1 itself, particularly at TiO₂ content or HFSE trace elements.

In terms of variability between the different groups, the composition of the melt inclusions in major and trace elements and the composition of the whole rocks reveal, at first sight, a differentiation of the magma along the calc-alkaline series (Figs. 3, 5, 9a and b). Fractional crystallisation of several minerals thus seems to have played a major role in the evolution of major elements and incompatible trace elements in the Mombacho magmas (Fig. 5). To study the role played by fractional crystallisation in the differentiation of magmas from Gr. 1 to Gr. 3, the evolution of the composition of melt inclusions was modelled using Petrolog3 software (Danyushevsky and Plechov, 2011). The models were generated using the algorithms of Beattie (Beattie, 1993) for olivine and orthopyroxene crystallisation, Pletchov et al. (Pletchov and Gerya, 1998) for plagioclase crystallisation, Nielsen (Nielsen et al., 1988) for clinopyroxene crystallisation and Ariskin and Barmina (Ariskin and Barmina, 1999) for ilmenite crystallisation. These models are well calibrated for the magmas in this study and are also the ones used by Zurek et al. (Zurek et al., 2019) in the case of Masaya. Several tests were carried out by varying the pressure, oxygen fugacity, minerals and starting compositions and are discussed in Supplementary Material A, Table A.4. The most relevant are presented in Fig. 5. For these, the initial oxygen fugacity is $\text{FMQ} + 2.3$, and the pressure is 200 MPa consistently with our observations. The starting compositions are based on each TiO₂ extremes recorded by the melt inclusions in this study. For each extreme, we performed a model at constant pressure, and a model simulating crystallisation and ascent by modelling chemical equilibrium and decompression ($dP/dT = 2.5 \text{ MPa/}^\circ\text{C}$) (Fig. 5). Temperature varies from 1200 °C to 900 °C. Overall, it is possible to reproduce the chemical evolution in major elements of the melt inclusions from Gr. 1 to Gr. 3 starting from different basaltic compositions. The models produce clinopyroxene, orthopyroxene, plagioclase and ilmenite crystals in the same compositional range as the crystals of this study. However, only one of the models, based on the composition with the lowest TiO₂ content and decreasing pressure during crystallisation produces olivine. In general, the modelling performed with a pressure decrease makes it possible to go to higher SiO₂ contents and to better reproduce the data from this study up to Gr. 3. The modelling performed without a pressure decrease stops earlier because the MgO is exhausted. In detail, the FeO and Al₂O₃ contents of the melt inclusions are very well reproduced up to Gr. 3 (Supplementary Material A, Fig. A.2). The MgO, TiO₂ and CaO contents are quite well reproduced, while the Na₂O and K₂O contents are much less well reproduced (Supplementary Material A, Fig. A.2). From Gr. 2 onwards, the models overestimate the Na₂O content and underestimate the K₂O content. Another point that is not explained by the fractional crystallisation process is the variability observed within Gr. 1, for which another process must be invoked. Analyses and modelling of major elements can give an important idea of the processes that can take place within a magmatic system, but these models are not necessarily exact and are based on choices and assumptions as oxygen fugacity or starting pressure (Supplementary Material A, Table A.4). This is why trace element analyses have been carried out, as they are more sensitive to the different magmatic processes and enable them to be distinguished more clearly. The K₂O vs. Co and K₂O vs. Sr graphs (Fig. 9a and b) also highlight the fractional crystallisation of olivine, orthopyroxene and plagioclase crystals and confirm what was deduced from the major element contents of the melt inclusions. The decrease in Co content of the melt inclusions in conjunction with the increase in K₂O content, i.e. differentiation, highlights the crystallisation of olivine and orthopyroxene crystals from Gr. 1 to Gr. 3 (Fig. 9a) as Co is highly compatible with these minerals (Rollinson, 1993). Similarly, the decrease in Sr

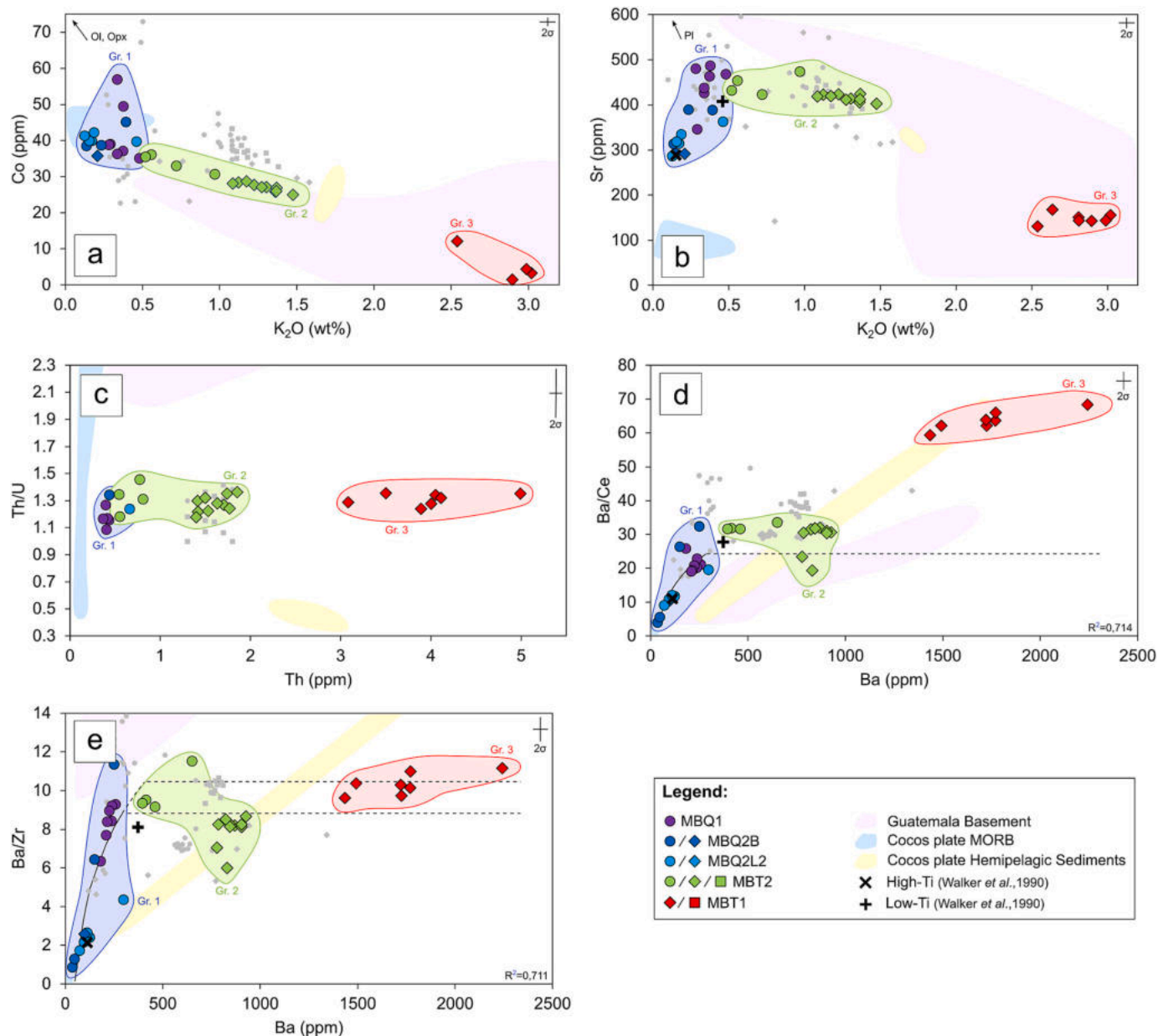


Fig. 9. Trace elements compositions of MIs. The R^2 presented in d. and e. are those of the curved lines. The curved lines are logarithmic trend curves passing through the melt inclusions of Gr. 1. Dotted lines are fractional crystallisation trends. Grey symbols are MIs data from the Masaya (Zurek et al., 2019) and Cerro Negro (Venugopal et al., 2016). The data used to define the continental crust, sediment and MORB fields come from Heydolph et al. (Heydolph et al., 2012) and Patino et al. (Patino et al., 2000).

content in the melt inclusions highlights the crystallisation of plagioclase crystals, this time only from Gr. 2 to Gr. 3, which is consistent with the first plagioclase crystals observed belonging to Gr. 2.

The inter-group variability has been explained by fractional crystallisation, but this process cannot explain the intra-group variability presented by Gr. 1. In Gr. 1, which represents the most primitive terms in the sequence, compositional variability is visible, mainly in TiO₂, volatile and some incompatible trace elements at constant SiO₂ or K₂O (Figs. 5, 6, 7 and 9). The melt inclusions have TiO₂ contents ranging from 0.64 to 1.50 wt%, reminiscent of the chemical variability observed by Walker et al. (Walker et al., 1990) in Nicaraguan basalts. These authors observed a variability in TiO₂ linked to the existence of two magmatic series: a relatively low-titanium series with contents between 0.55 and 0.89 wt% TiO₂ called low-Ti and a relatively titanium-rich series with contents between 1.13 and 1.26 wt% TiO₂ called high-Ti (whole rocks study). These values are of the same order of magnitude

as those measured in the melt inclusions of this study. Thus, compositional variability observed within Gr. 1 could be explained by a mix between low-Ti and high-Ti magmas. According to Walker et al. (Walker et al., 1990), the TiO₂-poor source reflects the greater influence of the subducted plate during the melting of the mantle wedge (at the origin of HFSE depletion in related magmas).

In order to ascertain the source of the compositional variability in Gr. 1, the trace element content of the melt inclusions was investigated. In the Th vs. Th/U graph, the Th/U ratio is constant, so contamination is ruled out (Fig. 9c). Even more so as the data do not tend towards any of the potential contaminant poles represented. The elements Ba and Ce (Fig. 9d) were chosen because of their incompatibility with the various minerals involved in the evolution of the Mombacho magmas. In the Ba vs. Ba/Ce graph, samples MBQ1, MBQ2B and MBQ2L2 (Gr. 1) form a curve in this graph representing a mixing curve (Fig. 9d). This curve also contains the high-Ti pole of Walker et al. (Walker et al., 1990) and seems

to be extendable towards the low-Ti pole suggesting a mixing between two mafic magmas, more or less rich in TiO_2 . Samples MBT2 (Gr. 2) and MBT1 (Gr. 3) differ from this curve and each form a straight line extending horizontally from this mixing curve, highlighting fractional crystallisation processes (Fig. 9d). These two samples do not line up on the same straight line highlighting another process behind the shift of Gr. 3 in the Ba vs. Ba/Ce graph.

Finally, a depletion in some trace elements is noted in Gr. 3 with respect to Gr. 1 and 2 (Supplementary Material B, Table B.2; Fig. 7). This is the case for incompatible elements as Ce, Nb, Y and Pb, that are present in the same concentration in Gr. 2 and 3 whereas they are supposed to be more concentrated in Gr. 3. Some incompatible elements are even less concentrated in the melt inclusions of Gr. 3, e.g. Sr, Cu and HREEs. These incompatible elements are relatively mobile and could have left in an aqueous fluid phase before the eruption (Webster et al., 1989; Iveson et al., 2019). According to Webster et al. (Webster et al., 1989), at 200 MPa Pb concentrates in the fluid phase and could therefore be depleted in the melt, as observed in the melt inclusions of Gr. 3 (Supplementary Material B, Table B.2). Similarly, the partition of Sr, Ce, Y and Nb into an aqueous fluid phase is enhanced by the Cl-enrichment of the latter at 800 °C and 200 MPa (i.e., similar pressure than given by our barometric estimates). Webster et al. (Webster et al., 1989) also indicate that the partitioning of lithophile elements in favor of the aqueous fluid phase is much greater if the latter does not contain CO_2 , which is the case for the Gr. 3 melt inclusions in this study. On the other hand, Ba partitions in the melt at 50–200 MPa and 800–950 °C (Webster et al., 1989), so that if Ce leaves in the aqueous fluid phase, Ba is expected to remain in the melt leading to an increase of the Ba/Ce ratio as observed in the melt inclusions of Group 3 (Fig. 9d). The straight lines passing through the origin and the melt inclusions of Gr. 1 in the K_2O vs. H_2O graph (Fig. 6a) supports than an aqueous fluid phase formed at depth and that water saturated magmas are represented by Gr. 3. This line represents the theoretical evolution of the H_2O content of the melt during differentiation by fractional crystallisation and the melt inclusions of Gr. 3 are below it, suggesting that some water has left. The same applies to chlorine, where a relative depletion is also observed (Fig. 6c). This depletion would indicate that chlorine has left the aqueous phase, which, according to Webster et al. (Webster et al., 1989), increases the affinity of lithophilic trace elements for the aqueous fluid phase. Alkaline elements may behave in the same way and complex with Cl in the aqueous phase, which could also explain the depletion of Na_2O in the melt inclusions of Gr. 3. So, to retrieve early magmatic processes acting for the chemical signature of Gr. 3, it is necessary to look at immobile elements (like Zr). Looking at the ratio of incompatible and immobile Ba/Zr trace elements (Fig. 9e), it can be observed that the samples from Gr. 1 form a mixing curve from which a crystallisation line starts. This straight line is made up of samples from Gr. 2 and 3, which seem to come from the same mafic magma, the latter being closer to the low-Ti end-member.

5.3. Degassing process

5.3.1. Volatile element behavior

Dissolved H_2O content in melt inclusions may be related to the distinct magmatic series (with lower H_2O in high-Ti magmas, sample MBQ2L2) or to the effect of early degassing of H_2O prior to the entrapment of some melt inclusions (Fig. 6a). This last phenomenon is even more viewable for melt inclusions from Gr. 2 with an almost constant (if not decreasing) dissolved H_2O content despite the increase of K_2O content (used as differentiation tracer). Even if a slight dissolved H_2O enrichment is observed in Gr. 3 with respect to Gr. 2, related to advanced crystallisation, a similar process is observed for Gr. 3 (Fig. 6a).

The evolution of dissolved S content is more complex (Fig. 6b and d). The sulfur concentration at sulfide saturation (SCSS) is calculated according to the model of Li and Zhang (Li and Zhang, 2022) and provides information on whether the system is saturated or not in S^{2-} . This model

considers the presence of sulfides into the melt. As the composition of the sulfides (that are chalcopyrite, Supplementary Material A, Fig. A.3) was not determined in this study, an average value of $\text{Fe}/(\text{Fe} + \text{Cu} + \text{Ni}) = 0.7$ is considered on the basis of the sulfide composition found in andesitic products of the Cosigüina volcano (also part of the CAVF; (Longpré et al., 2014)). The melt inclusions with a S content above the SCSS represent magmas oversaturated with S^{2-} , while those below indicate S-loss by degassing. Melt inclusions of Gr. 1 present an important variability in S content but most of them are above the SCSS and are therefore saturated or oversaturated in S^{2-} (Fig. 6d) which is consistent with a storage pressure around 200 MPa (Table 3). Most of the melt inclusions of Gr. 2 are also above the SCSS and present S^{2-} oversaturated compositions which agrees with the sulfide globules observed in some melt inclusions (Fig. 6d). The sulfur content of the melt inclusions of the Gr. 2 is lower than the Gr. 1 and decrease to the S content of the melt inclusions of the Gr. 3, which is very low. From Grs. 1 and 2 to Gr. 3, the S content decreases with the SCSS, showing a decreasing in S-solubility between Gr. 2 and Gr. 3. That could be linked (1) to a pressure drop (Lesne et al., 2011; Beermann et al., 2015) or (2) to the crystallisation of titanium-iron oxides which reduced the iron quantity in the magma, and consequently the solubility of sulfur (Gennaro et al., 2020). The sulfur concentration at anhydrite saturation (SCAS) was also calculated according to the model of Zajacz and Tsay (Zajacz and Tsay, 2019), indicating whether the system is saturated in S^{6+} . According to the model of O'Neil and Mavrogene (O'Neill and Mavrogenes, 2022), a total sulfur saturation (SCSS-SCAS_T) including both S^{2-} and S^{6+} was calculated too. The S content of all the melt inclusions lies below the SCAS and SCSS-SCAS_T, indicating that the melts trapped in the inclusions are not totally saturated with sulfur. As a result, the second hypothesis stipulating that the decrease in S-solubility between Gr. 2 and 3 is linked to the crystallisation of titanium-iron oxides is more appropriate. This hypothesis is supported by the sharp drop in FeO and TiO_2 content in the melt inclusions between Gr. 2 and 3 (Fig. 5a and b). In addition, the models of fractional crystallisation presented in Fig. 5 are performed with the crystallisation of ilmenite, a titanium iron oxide, and reproduce well the major element contents of the melt inclusions in this study. The S saturation pressure is estimated at around 100 MPa for Masaya volcano, a basaltic edifice neighboring Mombacho, by Lesne et al. (Lesne et al., 2011). Therefore, the melt trapped by the inclusions in Gr. 2 is expected to be at a higher pressure than this sulfur saturation pressure. The melt inclusions in Gr. 3, on the other hand, are almost saturated, and therefore closer to this pressure of 100 MPa. This is consistent with the architecture of the magmatic system established by the composition of the clinopyroxene crystals and the solubility of H_2O and CO_2 , which indicates that the magmas of Gr. 2 were stored at around 140 ± 170 MPa and those of Gr. 3 were stored between 190 and 80 ± 10 MPa (Table 3). Some of the inclusions in Gr. 3 have a storage pressure close to, or even below, the saturation pressure of the S, indicating that some of the inclusions in Gr. 3 may have been degassed by simple decompression.

The evolution of the dissolved Cl content in melt inclusions from Gr. 1 to Gr. 3 is much clearer with a positive correlation between Cl and K_2O , both elements acting as incompatible elements during melt differentiation (Fig. 6c). Although the Cl content of the melt inclusions increases with K_2O , it does not follow the theoretical line for the evolution of Cl content during differentiation by pure fractional crystallisation. This seems to indicate that, although fractional crystallisation took place and concentrated the Cl in the melt, some of it left early in the fluid phase, probably with H_2O . Spilliaert et al. (Spilliaert et al., 2006) indicate that the Cl exsolution pressure is around 100 MPa. Also, the inclusions in Gr. 2 and 3 that seem to indicate a loss of Cl are close to, or in some cases above, this pressure, which agrees with the storage pressures obtained by H_2O solubility and clinopyroxene crystals composition. This validates that the magmas in these groups are stored between 190 and 80 ± 10 MPa (Table 3).

5.3.2. Degassing modelling

In order to gain a better understanding of degassing processes at Mombacho, the evolution of the composition of the gas phase during magma ascent was modelled using the Sulfur_X program (Ding et al., 2023). Three models are presented to cover the different possible scenarios (Fig. 10) with a starting magma composition representative of either Gr. 1, Gr. 2 or MBQ1 (low-Ti end-member of Gr. 1). The choice of models and the parameters used are detailed in Supplementary Material A, Table A.5. The last scenario is the only one to consider degassing coupled with fractional crystallisation to simulate the ascent of a mafic low-Ti magma that differentiates during degassing (to form Gr. 3-type melts). Fractional crystallisation of silicate minerals is simulated using data from Fuego, a volcano that is also part of CAVF, whose composition is close to the one of Mombacho and for which major element variations of the magma in function of the degree of crystallisation is known (Lloyd et al., 2013). Fractional crystallisation is controlled by the empirical relation between H_2O and K_2O (assumed perfectly incompatible) defined by Loyd et al. (Lloyd et al., 2013) and the evolution of major element is empirically parametrized as a function of the degree of crystallisation (Rasmussen et al., 2020; Lloyd et al., 2013). For the three models runs, the maximum S, Cl and H_2O contents of each group of samples are initialized. The oxygen fugacity is set at FMQ + 2.3 for models starting from Gr. 1 and MBQ1 (low-Ti end-member of Gr. 1) because it is the one corresponding to the mafic magmas of Mombacho, and at FMQ + 2.1 for model starting from Gr. 2.

CO_2/S_T ratios measured in volcanic gases are often used to infer degassing depths in volcanic arc systems (Aiuppa et al., 2016; Aiuppa et al., 2017). CO_2 exsolves at greater depths than sulfur, so an increase in the CO_2/S_T ratio may indicate deeper, more juvenile degassing. The wide range of values covered by the fumarole gas data reveals the influence of the Mombacho hydrothermal system on sulfur concentrations (Fig. 10; Table 2). Through a phenomenon known as scrubbing, the SO_2 trapped by the waters of the hydrothermal system is dissolved without being emitted, thus artificially increasing the CO_2/S_T ratio measured (Symonds et al., 2001). So, to discuss degassing, it is necessary to refer to the measurement least affected by scrubbing, i.e. the lowest CO_2/S_T ratio which is 2.8. This ratio is very close to the one of 2.7 measured about twenty years ago by Garofalo et al. (Garofalo et al., 2007) showing that what is currently degassing is at the same pressure, i.e. at the same depth than in the early 2000s. Furthermore, using the lowest ratio measured in 2024, our model suggests magma degassing between 130

and 230 MPa. This pressure range overlap the one estimated by our barometric estimates (210 ± 50 – 80 ± 10 MPa). It highlights that the current source of degassing corresponds to the magmatic storage zone involved in the last eruptions, the dates of which are not known. The lowest ratio measured at Mombacho is very close to that of the Masaya (2.6; (Martin et al., 2010)) which has no hydrothermal system, and it therefore shows that it is not affected by the scrubbing phenomenon.

5.4. Conceptual model

Based on the results of this study, a first conceptual model of the architecture and functioning of the magmatic system related to the long-dormant volcano of Mombacho is proposed (Fig. 11). Barometric data based on clinopyroxene crystals composition, H_2O - CO_2 solubility and volatile elements behavior indicate a superficial storage zone, located between 8.2 ± 1.6 km and 3.1 ± 0.4 km. Within this large storage zone, it is not possible to clearly distinguish several levels of storage, but generally, the most mafic magmas (Gr. 1) and the intermediate ones (Gr. 2) appear to be at the base of the zone, while the most differentiated magmas (Gr. 3) appear to be found throughout the height of the zone.

Thus, at the base of this storage zone, at a depth of 8.2 ± 1.6 km, basaltic magmas (Gr. 1) intrude (Fig. 11, 1). These magmas may be low-Ti or high-Ti, or a mixture of the two in variable proportions. Regardless of their titanium content, these basaltic magmas have several possible futures. They can rise directly to the surface and form basaltic eruptions (Gr. 1) as testified by the small adventive cones distributed around the main edifice (Fig. 11, 2a). These magmas could also differentiate in the same storage zone until they reach intermediate composition (Gr. 2) and then be emitted to the surface (Fig. 11, 2b). Finally, the mafic magmas, as the intermediate ones, can stay at the same level or rise up shallower (up to 3.1 ± 0.4 km) to differentiate more (Gr. 3). During the crystallisation and the storage of the differentiated magmas, an early aqueous phase could form before the eruption, trapping the incompatible and mobile elements of the associated magmas which could be then emitted to the surface under the main edifice (Fig. 11, 2c).

In this main storage zone, evidence of magma mixing and recharge suggests a magmatic system where magma lenses are probably interconnected. Today, the gases emitted in the main Mombacho crater appear to come from this same shallow storage area. Barometric data also indicate that basaltic magmas (Gr. 1) come from a deeper storage zone located at 33 ± 7 km as said by van Wyk de Vries (van Wyk de Vries, 1993), which seems to be the depth of the Moho in this area (Manea et al., 2013).

6. Conclusion

The study of melt inclusions and clinopyroxene crystals of Mombacho has enabled us to acquire information about the evolution of magmas and their storage in order to build a conceptual model of the volcano. Analyses of the major and trace elements in the inclusions have highlighted the different processes involved in the evolution of magmas. Firstly, there is considerable variability within the most mafic compositions (Gr. 1), particularly in terms of TiO_2 content. This variability is attributed to the phenomenon described by Walker et al. (Walker et al., 1990) for which two magmatic series can be distinguished in Nicaraguan basalts: a relatively titanium-poor series (low-Ti) and a relatively titanium-rich series (high-Ti). The variability observed between them is attributed to variable degrees of mixing between these two poles, i.e. to more or less influence of the subducted plate during the melting of the mantle wedge. Secondly, from this range of mixing products, fractional crystallisation produces more differentiated magmas (Gr. 2 and Gr. 3). Thirdly, an aqueous chlorine-bearing fluid phase formed by early degassing, removing certain lithophile trace elements and possibly sodium from the magma.

Barometry based on the composition of clinopyroxene crystals, H_2O - CO_2 solubility and volatile elements behavior constrains magma storage

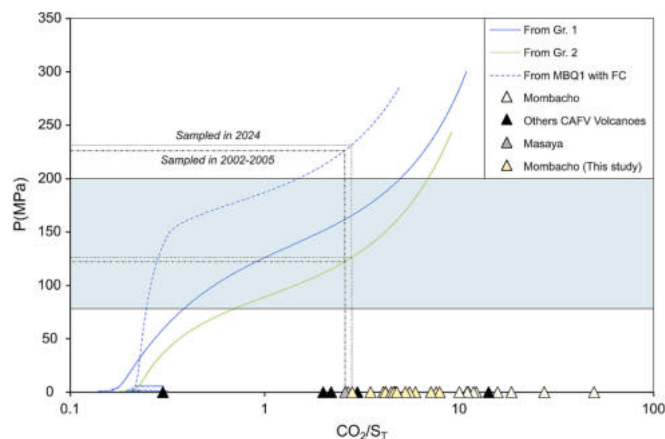


Fig. 10. Modelling of the evolution of the CO_2/S_T ratio in the co-existing gas phase during magma decompression/ascent. The ratios measured in the surface gases are also reported for Mombacho (Garofalo et al., 2007), Masaya (Martin et al., 2010) and other Nicaraguan volcanoes such as Momotombo (Menyailov et al., 1986), Telica and San Cristobal (Aiuppa et al., 2014). The blue range corresponds to the main superficial storage zone defined by H_2O - CO_2 and H_2O solubility. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

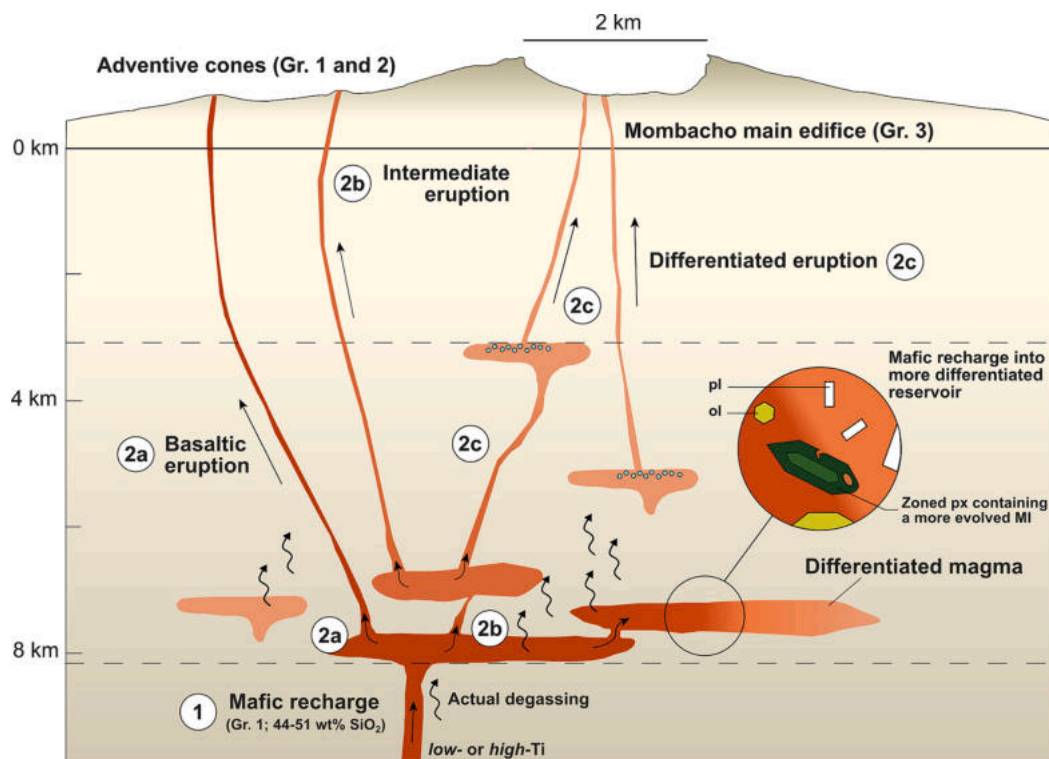


Fig. 11. Conceptual model of the volcanic system of the Mombacho based on melt inclusions, crystals and gases data. Blue circles represent the pre-eruptive aqueous gas phase. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

depths relative to these processes. There is a main shallow storage zone between 8.2 ± 1.6 and 3.1 ± 0.4 km. Several lenses, interconnected or not, can coexist in this storage zone. At the base, low-Ti or high-Ti basaltic recharges (Gr. 1) coming from the Moho are injected and can mix to form the range from which fractional crystallisation takes place. Maybe into the same lens, or perhaps a bit shallower, the magmas differentiate by fractional crystallisation (Gr. 2 and 3). Mafic or slightly differentiated magmas (Gr. 1 and 2) tend to rise towards the surface via preferential fracture zones controlled by local tectonics to form adventive cones. Magmas that have had time to differentiate (Gr. 3) tend to rise to the level of the main Mombacho edifice.

Based on this information and our modelling, the current surface gas emissions seem to come from the large identified shallow storage zone. However, it is not possible to be more precise due to the scrubbing phenomenon, which limits interpretations. In view of these conclusions and the analysis of current gaseous emissions, it seems that the renewed activity noted at Mombacho is not necessarily due to a resumption of magmatic activity. However, the possibility of renewed activity cannot be ruled out, which is why the volcano needs to be monitored more closely. Furthermore, if the reason for the renewed activity is not magmatic, it would be necessary to explore a tectonic or destabilization cause, in order to understand what the real risks are for the surrounding populations and towns.

CRedit authorship contribution statement

Manon Pouget: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **S  verine Moune:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization. **David Chavarria:** Investigation, Formal analysis. **Fausto Grassa:** Investigation, Formal analysis. **Martha Ibarra:** Investigation. **Etienne M  dard:** Writing – review & editing, Formal analysis. **Federica Schiavi:** Writing – review & editing, Methodology, Formal analysis. **Cristhian**

Torrez: Investigation. **Benjamin van Wyk de Vries:** Writing – review & editing, Supervision. **Guillaume Boudoire:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jvolgeores.2026.108571>.

Data availability

The original contributions presented in the study are included in the article and in Supplementary Materials. Further inquiries can be

directed to the corresponding author.

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