The 2013 eruption of Chaparrastique volcano (El Salvador): Effects of magma storage, mixing, and decompression

Piergiorgio Scarlato, Silvio Mollo, Elisabetta Del Bello, Albrecht von Quadt, Richard J. Brown, Eduardo Gutierrez, Bettina Martinez-Hackett, Paolo Papale

1. Introduction

El Salvador is one of the most seismically-active regions on Earth (Fig. 1a), being located along the Central American volcanic front that is defined by ~50 major volcanic centers, including composite or clustered volcanoes, distributed nearly continuously along 1200 km from western Guatemala to central Panama (e.g., Carr et al., 1979; Carr, 1984; MacMillan et al., 2004). The Volcanic Cordillera in El Salvador is a line of volcanoes parallel to the coast and the offshore subduction zone. El Salvador has 23 volcanoes and 5 volcanic fields. At present, only a few volcanoes are active (outgassing and rarely ash emissions) such as the Santa Ana, San Salvador, San Miguel and Izalco volcanoes (e.g., Agostini et al., 2006 and references therein).

Chaparrastique volcano, also known as San Miguel, is a composite volcano in central-eastern El Salvador, ~15 km southwest of the city of San Miguel. A rural population of ~70,000 people lives within 10 km of the summit crater of Chaparrastique, and San Miguel is the second...
largest city in El Salvador. On December 29, 2013, after 12 years of inac-
tivity, Chaparrastique volcano erupted at 10:30 local time (16.30 GMT),
prompting the evacuation of more than ~5000 people living in ~3 km
radius around the volcano (Martinez-Hackert et al., 2015). The eruption
was a volcanic-type explosion that lasted 2.5 h (Fig. 1b). The explosion
was classified as VEI 2 and produced an ash plume with a maximum
height of ~9 km (Martinez-Hackert et al., 2015). The eruption column
generated heavy ash fall in nearby areas downwind, especially in the
towns of Chinameca and San Jorge. A short lived pyroclastic density cur-
rent generated from an early Vulcanian explosion travelled ~500 m
down the flanks of the volcano and entered coffee plantations.

On January 2014, in response to a request of support by the govern-
ment of El Salvador, the INGV (Istituto Nazionale di Geofisica e
Vulcanologia, Italy) organized a task force in close collaboration with
volcanologists from MARN (Ministerio de Medio Ambiente y Recursos
Naturales, El Salvador). A campaign survey was conducted over a period
of ten days, with the aim to install a monitoring network on the
flanks of the volcano (Bonforte et al., 2015; Granieri et al., 2015; Scarlato et al.,
2014). At the same time, a suite of twelve eruptive products (i.e., fallout
tephra) was collected in correspondence of the seismic monitoring sta-
tions of VSMG, RANC, and LACA located, respectively, at 1 km north, 2 km east, and 3 km south-east to the volcanic crater where twelve rock samples were collected (c).

Here we present textural and mineral chemistry data from pheno-
crys integrated with bulk rock geochemical and isotopic data, with
the aim to elucidate magmaic processes that triggered the 2013 erup-
tion. Mineral-melt equilibria, and major and trace element modelling
define the pre-eruptive crystallization conditions of the system and in-
dicate that magma mixing and magma decompression were the most
important mechanisms for triggering the eruption. The magma source
has been also constrained by trace element and isotope systematic.
Magmas were generated by partial melting of an enriched MORB-like
mantle wedge with a dominant contribution of aqueous fluids derived
from the subducted slab.

2. Geological setting

The Pacific coastline of much of Central America is marked by a line
of active and quiescent volcanoes known as the Central American Volca-
nic Arc (CAVA) (e.g., Aubouin et al., 1982; Carr et al., 1990, 2004;
Leeman et al., 1994; Protti et al., 1995). To the south of Central America
the Cocos Plate, which underlies an area of the east Pacific, is being
subducted beneath the Caribbean Plate along the Middle American
trench. The volcanoes result from the upward movement of magma
generated along the subduction zone between the Cocos and Caribbean
tectonic plates. El Salvador, and neighbouring Central American states,
lies on the Caribbean Plate. Frequent earthquakes also occur along the
plate boundary. From Guatemala to northern Costa Rica, ~25 Ma old
crust (formed at the East Pacific Rise) is subducted at an angle varying
from 55° in Guatemala and El Salvador to 65° in Nicaragua and northern
Costa Rica (Protti et al., 1995; Syracuse and Abers, 2006). The crustal
thickness, angle of subduction, and convergence rate contribute to the
thermal structure of the subduction zone, which is a major control on
the generation of magmas in Central America (Davies and Stevenson,
1992). The sediment input consists of a ~200-m-thick layer of
hemipelagic clay overlying a ~250-m-thick layer of carbonate ooze
compositions of volcanic rocks from CAVA record systematic along-
strike variations in many geochemical tracers of the slab, including Ba/
La (Carr et al., 1990), U/Th (Patino et al., 2000), B/Be (Leeman et al.,
1994), and δ18O (Eiler et al., 2005). For most of these tracers, the peak
in inferred slab flux occurs in the central portion of the CAVA, in Nicara-
gua, and falls to nearly the global minimum to the southeast, at the ter-
minal sector of volcanoes of Costa Rica. Where the crust is thinner, high-
Mg basalts are more abundant (e.g., Nicaragua). Conversely, in cor-
respondence of a thick and old continental crust, low-Mg basaltic lavas
occur and are less abundant (e.g., central and western Guatemala).
Moreover, the continental crust of southern Central America is

![Fig. 1. Schematic map showing the Central American volcanic arc (CAVA), where volcanism occurs above the plate boundary between the subducting Cocos plate and the overriding Caribbean plate (a). The ash plume of the Chaparrastique vulcanian-type eruption captured by the Suomi NPP satellite (b). Seismic monitoring stations of VSMG, RANC, and LACA located, respectively, at 1 km north, 2 km east, and 3 km south-east to the volcanic crater where twelve rock samples were collected (c).](image-url)
relatively young and thin, compared to the crust of other continental margins, making it less radiogenic (Carr, 1984; Donnelly et al., 1990).

Chaparrastique volcano in eastern El Salvador is a 2130 m-high symmetrical stratovolcano with a broad, deep crater complex, which has frequently changed morphology during historic eruptions (Escobar, 2003). Chaparrastique is considered one of the most active volcanoes in El Salvador, with 26 eruptions in the past 500 years. Seismic activity is high, while surface activity consists of pulsating gas emissions that ascend to maximum heights of ~200 m. On December 29, 2013, the volcano erupted –80 vol% of crystal-free juvenile material (shards of fresh glass and crystal fragments) associated with ~20 vol% of lapilli and scoria clasts. The eruption formed a new spatter cone in the central crater. In the days that followed, the SO2 emissions were estimated to reach 2800 tons per day. The increasing tremor and gas emissions also suggested migration of hot fluids (gas, water, and magma) into the shallow plumbing system of the volcano. Before such event, the eruptive history of Chaparrastique was characterized by the occurrence of modest VEI 1–2 eruptions (search for Chaparrastique at the MARN’s webpage http://www.marn.gob.sv), mainly attributed to spattering and scoria cones at the flanks, and minor Strombolian and ash eruptions in the summit crater (Chesner et al., 2004). Since the 29 December eruption, Chaparrastique has experienced periods (from May to July 2014) of increased seismic and degassing activity, landslides inside the crater, and lahars. Occasionally, small steam/phreatomagmatic explosions and minor ash falls have occurred, but no substantial explosive events have been reported. However, the level of alert remains high and explosions of small to moderate size similar to the 29 December event remain a possibility.

3. Methods

Textural and microchemical analyses were carried out at the HP-HT Laboratory of Experimental Volcanology and Geophysics of the Istituto Nazionale di Geoﬁsica e Vulcanologia in Rome (Italy). Images were collected using the backscattered electron (BSE) mode of a ﬁeld emission gun-scanning electron microscope (FE-SEM) Jeol 6500F equipped with an energy-dispersive spectrometer (EDS) detector. Microchemical analyses were performed using an electron probe micro-analyzer (EPMA) Jeol-JXA8200 combined EDS-WDS (ﬁve spectrometers with twelve crystals) with 15 kV accelerating voltage and 10 nA electric current. For glasses, a slightly defocused electron beam with a size of 3 μm was used, with a counting time of 5 s on background and 15 s on peak (Table 1S). For crystals, the beam size was 1 μm with a counting time of 20 and 10 s on peaks and background, respectively (Table 1S). The following standards have been adopted for the various chemical elements: jadeite (Si and Na), corundum (Al), forsterite (Mg), and andradite (Fe), rutile (Ti), orthoclase (K), barite (Ba), apatite (P), spessartine (Mn) and chromite (Cr). Sodium and potassium were analyzed ﬁrst to prevent alkali migration effects. The accuracy of the microprobe was measured through the analysis of well-characterized synthetic oxides and mineral standards. Data quality was ensured by analyzing these test materials as unknowns. Based on counting statistics, analytical uncertainties relative to their reported concentrations indicate that precision was better than 5% for all cations.

Bulk rock analyses for major and trace elements, as well as oxygen isotope analyses were conducted at Actlabs ( Activation Laboratories Ltd.). These analyses are reported in the Supplementary material (Table 2S), together with measured and certiﬁed analyses of international reference materials. Major elements were analyzed by lithium metaborate/tetraborate fusion – ICP-OES (inductively coupled plasma optical emission spectrometry). Sample washing was performed to remove any organic, loosely adhered, and cementing material. Washing included soaking in a hot mixture of HCl and H2O2 as well as cleaning in acetone using ultrasound. The analyses were performed in a batch system. Each batch contained a method reagent blank, certiﬁed reference material and 17% replicates. Samples were mixed with a ﬂux of lithium metaborate and lithium tetraborate and fused in an induction furnace. The molten material was immediately poured into a solution of 5% nitric acid containing an internal standard, and mixed continuously until completely dissolved (about 30 min). The samples were run on a Thermo Jarrell-Ash ENVIRO II ICP. Calibration was performed using 7 prepared USGS and CANMET certiﬁed reference materials. FeO was determined through titration, using a cold acid digestion of ammonium metavanadate, and hydroﬂuoric acid in an open system. Ferrous ammonium sulphate was added after digestion and potassium dichromate was the titrating agent. This cold digestion dissolved silicates and some sulphides. Water content was determined by gravimetric method. About 0.3 g sample was thermally decomposed in a resistance furnace in a pure nitrogen environment at 110 °C (moisture, H2O−) followed by decomposition at 1000 °C (intertstitial water, H2O+), using an ELTRA CW-800, directly releasing H2O. Trace elements were measured by lithium metaborate/tetraborate fusion – ICP-MS (inductively coupled plasma mass spectrometry). Samples fused as reported above were diluted and analyzed by Perkin Elmer Sciex ELAN 6000, 6100 or 9000 ICP/MS. Three blanks and five controls (three before sample group and two after) were analyzed per group of samples. Oxygen isotopes are measured by reaction with Br2 at about 650 °C in nickel bombs. The ﬂuorination reaction converts O in the minerals to O2 gas, which is subsequently converted to CO2 gas using a hot C rod. All reaction steps are quantitative. Bulk rock isotopic analyses are performed on a Finnigan MAT Delta, dual inlet, isotope ratio mass spectrometer. The data are reported in the standard delta notation as per mil deviations from V-SMOW (hereafter reported as to SMOW). External reproducibility is ±0.1‰ (1 s).

The isotopic compositions of Sr and Nd (Table 2S) were measured at the ETH Zürich using a Triton Plus thermal ionization mass spectrometer (TIMS). Details of analytical techniques, accuracy and precision can be found in von Quadt (1997). The isotopic analysis set for Sr and Nd was performed on bulk rock powder (50–100 mg). Values for 87Sr/86Sr were internally corrected for fractionation using a 88Sr/86Sr value of 0.11945. Repeated measurements of the NBS 987 standard for 88Sr/86Sr gave a mean value of 0.710252 ± 0.000002 (2σ). 143Nd/144Nd values were internally corrected for mass fractionation using a 146Nd/144Nd value of 0.7219. No correction on Nd was performed due to good segregation of Nd and Sm during column chemistry. Repeated measurements on the Nd Merck standard for 146Nd/144Nd gave a mean value of 0.511730 ± 0.000019 (2σ). The analytical uncertainties associated to the Sr and Nd isotopic compositions of our samples are in the range of 0.000006–0.000019 and 0.000002–0.000012, respectively.

4. Mineralogy, petrology and geochemistry

Mineral chemistry, petrology and geochemistry was performed in twelve samples of juvenile material and scoria clasts ejected during the 2013 eruption. The juvenile material consists of white-grey coarse ashes and dark-grey accretionary lapilli (i.e., CH1, CH2, CH4, CH5, CH8, CH10, CH11, and CH12 samples), and are associated to centimetre-sized scoria clasts containing phenocrysts and microlites surrounded by matrix glass (i.e., CH3, CH6, CH7, and CH9 samples). Mineral and matrix glass analyses of scoria clasts are reported in Table 1S submitted as Supplementary material. Bulk rock analyses of the juvenile material and scoria clasts are reported in Table 2S submitted as Supplementary material. Major and trace elements were measured for all the bulk rock samples, whereas radiogenic and stable isotopes were analyzed only for CH1, CH2, CH4, CH9, and CH12 samples that represent the entire bulk rock compositional variation.

4.1. Textures of scoria clasts

The paragenesis of scoria clasts is dominated by phenocrysts of olivine and plagioclase (~23 vol%), and minor pyroxene and spinel (~7 vol%). The groundmass consists of plagioclase, pyroxene, and spinel microlites (~12 vol%), surrounded by matrix glass (~58 vol%). The
relatively low microlite content suggests that, at the time of eruption, late crystallization was hampered by rapid quenching of magma.

The habit of olivine is generally euhedral with well-formed planar edges. Larger olivine phenocrysts are poikilitic and enclose sub-rounded spinels (Fig. 2a), whereas smaller olivines are accompanied by spinel phenocrysts with irregular boundaries and glass embayments resulting from the agglomeration of bleb-like grains (Fig. 2b).

Pyroxene crystallized as both sub-euhedral orthopyroxene and clinopyroxene. Orthopyroxenes are less frequently observed but sometimes occur as large phenocrysts partly enclosing small clinopyroxenes (Fig. 2c).

Plagioclase is characterized by complex zoning in which the cores, mantles and rims are separated by sharp interfaces. BSE images reveal (1) dark-grey, partly corroded cores, (2) light-grey, coarsely sieve-textured mantles, and (3) grey, euhedral to sub-euhedral rims (Fig. 2d–f). Notably, detailed BSE images of the plagioclase rims show that their final euhedral habit results from the attachment of a number of groundmass microlites growing as tabular crystals (Fig. 2g–i). These small, elongated plagioclases attach preferentially parallel preferentially parallel to the longest crystal dimension that normally corresponds to the [100] crystallographic direction contributing to the textural maturation of the rim. In contrast, plagioclase mantles are characterized by the occurrence of micrometre-sized glass channels and hollows, sometimes, in full communication with the matrix glass when the growth of the crystal rim results incomplete.

4.2. Mineral and glass chemistry of scoria clasts

Olivine is normally zoned with forsterite (Fo) contents decreasing from core-to-rim. Larger poikilitic olivines enclosing spinels show Fo_{77-79} cores and Fo_{74-76} rims (Fig. 2a). The olivine core is also more calcic (0.51–0.63 wt.% CaO) than the rim (0.32–0.56 wt.% CaO). Conversely, smaller olivines mutually touching with spinels in the matrix glass are weakly zoned with Fo_{74-75} cores and Fo_{72-73} rims (Fig. 2b).

Spinel is titanomagnetite with variable ulvospinel content (Usp). Smaller, sub-rounded titanomagnetites enclosed in olivine are Usp_{24-27} (Fig. 2a), whereas single, isolated titanomagnetites are Usp_{21-19} (Fig. 2b). Titanomagnetites in poikilitic olivines are also more primitive (~6–7 wt.% MgO) than those found in the matrix glass (~4–5 wt.% MgO).

Pyroxene is both orthopyroxene and clinopyroxene. Orthopyroxene exhibits weak chemical variation with a narrow enstatite (En) content of En_{60-63} (Fig. 2c). Clinopyroxene is augite (cf. Morimoto, 1988) with relative low-CaO concentration (~17 wt.%) and variable diopside (Di) content ranging from Di_{37} to Di_{46} (Fig. 2c).

Among all the minerals, plagioclase phenocrysts are characterized by important compositional changes reflecting the complex textural characteristics. Plagioclases are strongly reversely zoned with resorbed sodic cores surrounded by dusty sieve-textured calcic mantles. This suggests an origin by resorption and rapid re-growth due to mixing between two compositionally distinct magmas. The anorthite (An) content sharply increases from core (An_{53-65}) to mantle (An_{80-84}). Conversely, at the final stage of the crystal growth, a thin-to-thick rim occurs with chemistry (An_{77-80}) intermediates between core and mantle compositions (Fig. 2d, e, f). Importantly, the rim chemistry is almost identical to that of groundmass plagioclases, suggesting coeval crystallization (Fig. 2g, h, i).

The matrix glass is 52.7–54.3 wt.% SiO_2 and 3.5–4.6 wt.% Na_2O + K_2O, corresponding to the composition of a basaltic andesite (i.e., Le Bas et al., 1986). However, Mg# (100 × molecular MgO/...
FeOtot + MgO) values are highly variable ranging from 25 to 43. Indeed, the glass analyses are not homogeneous showing concentration gradients especially next to the well-developed rims of large plagioclase phenocrysts (see discussion below). Within such chemical variability, the composition of the matrix glass does not differ substantially from that of micrometre-sized glass channels and glass inclusions within plagioclase phenocrysts.

4.3. Bulk rock geochemistry

On anhydrous basis, the products are calc-alkaline basalts (CH1-CH2) and moderately (CH3-CH6) to more differentiated (CH7-CH12) basaltic andesites (i.e., Le Bas et al., 1986; Fig. 3a) with medium-K affinity (i.e., Le Maitre, 2002; Fig. 3b). Bulk rocks align along one single trend in which both silica and alkali explore limited compositional variations (Fig. 3a-b). From CH1 to CH12, MgO and CaO linearly decrease from ~7 to ~3 wt.% and from ~11 to ~8 wt.%, respectively, reflecting the more evolved character of the samples.

The chondrite-normalized pattern (Sun and McDonough, 1989) of REE (rare earth elements; Fig. 3c) exhibits sub-parallel trends shifting towards progressive REE enrichments from CH1 to CH12. Slight enrichments in LREE (light rare earth elements) relative to HREE (heavy rare earth elements) are also observed. Bulk rocks are characterized by weak negative Eu anomaly (Eu/Eu* = 0.86–0.92) and relatively low values of normalized La/Yb ratios (2.8–3.1). The primordial mantle-normalized pattern (Sun and McDonough, 1989) of trace elements (Fig. 3d) shows typical features of arc magmas, with LILE (large ion lithophile elements) to HFSE (high field strength elements) ratios higher than the primitive mantle values. This is confirmed by low Nb and Ta concentrations and correspondingly high Ba/Ta (2900–4200) and La/Ta (62–80) ratios. The incompatible elements generally increase with increasing SiO2. Moreover, trace element patterns show positive spikes of Ba, U, K and Sr, and negative Nb, Ta, Ti, Hf and Zr anomalies. The compatible TE (transition elements) such as Ni (11–20 ppm) and Cr (20–58) are low and their concentration decreases from CH1 to CH12, in accordance with decreasing MgO.

Radiogenic isotope compositions of bulk rocks are constrained in narrow intervals of 0.70377–0.70387 and 0.51291–0.51299 for \(^{87}\text{Sr}/^{86}\text{Sr}\) and \(^{143}\text{Nd}/^{144}\text{Nd}\) ratios, respectively. According to isotope data from other volcanoes in El Salvador, the lack of sensible isotopic variations with the degree of magma evolution indicates that crustal contamination processes are likely to be minimal (Agostini et al., 2006).

Oxygen-isotope ratios range between 5.4 and 5.6‰, showing values comparable to most mantle peridotites (~5.5 ± 0.2‰; e.g., Mattey et al., 1994). However, it is important to note that the oceanic lithosphere is highly heterogeneous in \(\delta^{18}\text{O}\) and may contribute with slab-derived components with oxygen-isotope ratios (0–6‰) equal to or lower than typical upper mantle peridotites, i.e., hydrothermally altered lower oceanic crust and ultramafic rocks such as serpentinites (Cocker et al., 1982; Staudigel et al., 1995).

![Fig. 3. TAS (total alkali vs. silica; Le Bas et al., 1986) diagram showing calc-alkaline basalts (CH1-CH2) and moderately (CH3-CH6) to more differentiated (CH7-CH12) basaltic andesites (a). According to the SiO2 vs. K2O diagram (Le Maitre, 2002), the Chaparrastique volcanic products have medium-K affinity (b). The chondrite-normalized pattern (Sun and McDonough, 1989) of REE (rare earth elements) exhibits sub-parallel trends shifting towards progressive REE enrichments from CH1 to CH12 (c). The primordial mantle-normalized pattern (Sun and McDonough, 1989) of trace elements shows typical features of arc magmas, with LILE (large ion lithophile elements) to HFSE (high field strength elements) ratios higher than the primitive mantle values (d).](image-url)
5. Discussion

5.1. Magma crystallization conditions

In order to decipher the crystallization conditions of the erupted products, the olivine-based thermometer of Putirka (2005a) with a relatively low uncertainty of ± 27 °C has been used. Olivine-melt equilibria are particularly useful for temperature estimations because the Fe-Mg exchange reaction is nearly constant over a wide range of temperatures, bulk compositions and \( fO_2 \) conditions (i.e., ol-melt \( K_d_{Fe-Mg} = 0.30 \pm 0.03 \)), and because the olivine Fo content is highly sensitive to the thermal path of magma (e.g., Roeder and Emslie, 1970). Assuming that olivine is the liquidus phase, its early-formed core is expected to be in equilibrium with the original magma represented by the bulk rock analysis (cf. Putirka, 2008). Through this approach, it is found that Fo\(_{78-77}\) olivines are in equilibrium with the primitive basalts (MgO > 6 wt.%), yielding onset temperatures of 1135–1146 °C (Fig. 4a). Conversely, Fo\(_{74-75}\) olivines are in equilibrium with the more evolved basaltic anodesites (MgO < 4 wt.%), recording onset temperatures of 1067–1084 °C (Fig. 4a). The equilibrium condition is attained when the total Fe of the melt is partitioned between Fe\(^{2+}\) and Fe\(^{3+}\) through the formulation of Kress and Carmichael (1991), over buffering conditions relative to NNO (nickel-nickel oxide) and NNO + 1, respectively for Fo\(_{78-77}\) and Fo\(_{74-75}\) olivines. These different redox states have been predicted by the spinel-melt oxygen barometer of Ariskin and Nikolaev (1996), using high-Mg titanomagnetites hosted in Fo\(_{78-77}\) poikilitic olivines (Fig. 2a) and low-Mg titanomagnetites coexisting with Fo\(_{74-75}\) olivines (Fig. 2b). The distinct textural and chemical characteristics for olivine and titanomagnetite suggests mixing between a high-\( T \), mafic melt with \( fO_2 \) typical of the lower crust of volcanic arcs (Brounce et al., 2014) and a low-\( T \), differentiated melt with \( fO_2 \) commonly encountered in shallower, slightly more oxidized crustal reservoirs (see below).

With respect to plagioclase crystallization, the equilibrium model of Namur et al. (2011) indicates that the more sodic (An\(_{53-65}\)) core and the more calcic (An\(_{80-84}\)) mantle approach to equilibrium with more evolved (CaO ≤ 8 wt.%) and primitive (CaO ≥ 9 wt.%) bulk rocks, respectively (Fig. 4b). Conversely, the equilibrium condition is never found between the intermediate (An\(_{77-80}\)) plagioclase rim and the overall bulk rock compositions. The plagioclase rim is also in disequilibrium with the surrounding matrix glass (Fig. 4b) and data deviate from the one-to-one straight line, responding to moderate An enrichments in the plagioclase rim (ΔAn = 16–27%). The thermometer of Putirka (2005b) with uncertainties of ± 36 °C, yields crystallization temperatures of 1051–1063 °C, 1119–1129 °C, and 1098–1117 °C for plagioclase core, mantle and rim, respectively. These predictions account for minimum H\(_2\)O-melt concentration of 2 wt.% derived by the difference to 100% of the total of electron microprobe analyses of matrix glasses (cf. Devine et al., 1995). It has been also tested that H\(_2\)O contents up to 4 wt.% changes the temperature estimates by ± 32 °C that, however, remains within the relatively high uncertainty of the thermometer. The
occurrence of low-\(T\), partly resorbed cores surrounded by high-\(T\), sieve-textured mantles (\(\Delta T \approx 70{\text{ °C}}\)) confirms mixing between two compositionally distinct magmas. It is therefore inferred that a colder, basaltic andesitic magma reservoir was intruded by a hotter, basaltic magma rising from depth. The increase in \(\text{An}\) content for the plagioclase mantle supports the hypothesis that the new magma was compositionally more primitive and possibly hotter and/or wetter. The textural evidence of dissolution and patchy regions at the inner part of the plagioclase corroborates the mixing mechanism (e.g., Tsuchiya and Takahashi, 1983; Tsuchiya, 1985; Teply et al., 2000). Therefore, more evolved \(\text{FO}_{74-75}\) olivines and \(\text{An}_{30-45}\) plagioclases crystallized from a colder basaltic andesitic magma that, subsequently, mixed with the hotter basaltic magma rising from depth and carrying more primitive \(\text{FO}_{78-77}\) olivines. Pre-existing less calcic \(\text{An}_{30-45}\) plagioclases in contact with the recharging basaltic magma experienced an increase in temperature that resulted in resorption textures (Fig. 3d-f). While the contact and host magmas attempted to hybridize, high-temperature gradients lead to relatively rapid crystallization of sieve-textured, more calcic \(\text{An}_{80-84}\) mantles with the contribution of the more primitive component of the mixing system (e.g., Hibbard, 1981; Sherbakov et al., 2010). Coherently with this scenario, the weak negative europium anomaly of the bulk rocks excludes substantial plagioclase fractionation at depth (Fig. 3c).

By means of the two-pyroxene model of Putirka (2008), it is found that orthopyroxene and augite exhibit Fe-Mg exchange values (i.e., melt. On the other hand, at a low-\(T\), orthopyroxene. The lack of amphibole in the eruptive products is also in accordance with low-\(P\) crystallization conditions in which the amphibole saturation surface is encountered only at \(T \approx 950{\text{ °C}}\)

Magma mixing is recognized as a widespread process in calc-alkaline, arc-related magmas that contributes to magma chamber evolution and is a likely trigger for eruptions (Sparks et al., 1977; Eichelberger et al., 2000). Previous petrological studies on volcanoes along the CAVA have documented the role of magma mixing as the cause of substantial changes in major and trace element compositions (e.g., Streck et al., 2002; Richer et al., 2004). In particular, magma mixing has been observed for a number of volcanoes in El Salvador; generally between basaltic andesitic and andesitic magmas (e.g., San Vincente volcano), and between basaltic andesitic and rhyodacitic magmas (e.g., Ilopango volcano), leading to a variety of complex rock textures characterized by corroded/resorbed plagioclases and bimodal compositional distributions of phenocrysts (e.g., Carr et al., 2007 and references therein).

### 5.2. Magma mixing vs. magma fractional crystallization

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If magma mixing occurred at the time of Chapparrastique eruption, bulk rock compositions are expected to plot on tie-lines between CH1 and CH12 end-members, resulting to be rather different from the curved trajectories caused by fractional crystallization. To test this hypothesis, MELTS (Ghiorso and Sack, 1995) simulations have been conducted using the most primitive CH1 basalt as a starting liquid (Table 35 submitted as Supplementary material). Thermodynamic runs started from the superliquidus temperature of 1170 °C and continued along a fractional crystallization path that terminated at 1020 °C. The pressure, melt-H\(_2\)O content and oxygen fugacity were set at 200 MPa, 3 wt.%, and
NNO + 1, respectively, as the best input parameters reproducing the natural phase assemblage. Results show that the curved MELTS trajectories do not match in full with the natural Chaparrastique compositions that, in turn, align along tie-lines between CH1 and CH12 end-members (Fig. 6a). This is also true for the behaviour of trace elements modelled by the Excel spreadsheet of Ersoy and Helvacı (2010). The original partition coefficients set in the spreadsheet were used to derive the fractional crystallization vectors for REE (c), HFSE (b), and TE (d). While these vectors describe an implausible magmatic evolution for the Chaparrastique products, mixing (straight) lines joining CH1 and CH12 end-members successfully model the bulk rock variability.

5.3. Magma decompression and ascent to the surface

Plagioclase phenocrysts from Chaparrastique eruption exhibit partly resorbed An53–65 cores that are the herald of early equilibrium in a basaltic andesitic magma chamber, and sieve-textured An80–84 mantles interpreted as markers of further basaltic recharge (Fig. 2d, e, f and Fig. 4b). If the mixing efficiency is low, the influx of mafic magma, possibly transferring heat and H₂O, causes inverse zoning of plagioclase due to dissolution and overgrowth of highly calcic crystals (e.g., Tsuchiyama, 1985; Davidson and Tepley, 1997). Conversely, if the system rapidly re-equilibrates to form a homogeneous hybrid melt, an overall normally zoned trend is resumed with newly-formed calcic cores grading into sodic rims (e.g., Izbekov et al., 2004; Neill et al., 2015). Apparently, this latter mechanism seems to explain the final growth of An77–80 plagioclase rims and the crystallization of groundmass microlites (Fig. 3d-i). However, these late-stage plagioclases are not in equilibrium with the hybrid melt if its composition is assumed to correspond with the final matrix glass (Fig. 4b). Moreover, chemical profiles carried out far enough away from the plagioclase surface reveal that the matrix glass is not homogeneous (Table 4S), due to the development of chemical gradients at the crystal-melt interface (Fig. 7a).

Numerous cooling and decompression studies explored the effect of magma mixing and undercooling on the crystallization kinetics of plagioclase (e.g., Kirkpatrick et al., 1976; Smith and Lofgren, 1983; Muncill and Lasaga, 1987; Sato, 1995; Hammer and Rutherford, 2002; Couch, 2003; Pupier et al., 2007; Fiege et al., 2015). According to experimentally-derived data (Mollo et al., 2011, 2012a), if crystal growth rate is large compared with the rate of component diffusion in the melt, a diffusive boundary layer develops causing enrichments in elements incompatible with the plagioclase crystal lattice (Fig. 7a). Concentration-dependent partitioning produces plagioclases that respond to chemical...
gradients in the melt, so that crystals incorporate high Ti, Mg, and Fe proportions (Fig. 7a) and become preferentially enriched in An with respect to equilibrium crystallization (Fig. 4b). The effect of undercooling due to temperature decrease (cf. Mollo et al., 2011) and/or H$_2$O exsolution (cf. Brugger and Hammer, 2010) leads to the formation of disequilibrium An-rich plagioclases in response to the drastic change of the topology of the Ab-An plagioclase binary loop in which the temperature difference between liquids and solids is minimized (cf. Iezzi et al., 2014). It is interesting to note that disequilibrium plagioclases crystallizing from rapidly decompressed calc-alkaline melts in laboratory show An enrichments (ΔAn = 12–30%; data from Brugger and Hammer, 2010) very close to those (ΔΔAn = 16–27%) measured in this study. The control of undercooling is also evidenced by the attachment of groundmass microlites to form the plagioclase rim (Fig. 3g-i). This crystal growth mechanism has been documented under kinetically-controlled conditions by in-situ experimental observations (Schiavi et al., 2009), crystal size distribution analysis (Iezzi et al., 2011; Lanzafame et al., 2013), and electron-microprobe mapping (Iezzi et al., 2014). The attachment mechanism is possibly explained by heterogeneous nucleation events on the pre-existing crystal surface (Mollo et al., 2012b; Vetere et al., 2015) and/or by the emerging theory of aggregation by self-orientation of sub-micrometric crystals (Teng, 2013 and references therein).

An important consequence of the diffusion-controlled growth is that the partition coefficient measured between the advancing plagioclase surface and the diffusive boundary layer changes upon the effect of chemical gradients in the melt. The partition coefficient is expressed as:

\[ K_i = \frac{c_i^{true}}{c_i^{melt}} \]  

(1)

where \( c_i^{true} \) is the concentration of a chemical element \( i \) in the crystal and \( c_i^{melt} \) is the concentration of the same element in the melt. If the compositions of both crystal and melt result from interface-controlled growth and are supposed to be in equilibrium with respect to element exchange at the crystal–melt interface, Eq. (1) provides the ‘true’ partition coefficient \( K_i^{true} \). Conversely, the effect of diffusion-controlled growth is to change \( K_i^{true} \) in an ‘apparent’ partition coefficient \( K_i^{app} \) when the chemistry of the advancing crystal surface reflects the chemical concentrations in the diffusive boundary layer. During plagioclase disequilibrium growth driven by undercooling, it has been experimentally-derived that \( K_i^{true} < K_i^{app} \) and \( K_i^{true} < K_i^{fl} \) (Mollo et al., 2011). For the case of natural plagioclase phenocrysts, the lattice strain equation of Dohmen and Blundy (2014) represents a powerful tool to predict whether or not the partitioning of Mg is controlled by equilibrium or disequilibrium growth conditions. The model was derived by thermodynamic principles and allows to predict \( K_i^{eq} \) for a wide range of equilibrium plagioclase and melt compositions. The partitioning of Mg measured between sodic core (or calcic mantle) of plagioclase and CaO-poor (or CaO-rich) bulk rocks yields values close to those predicted by the lattice strain equation of Dohmen and Blundy (2014). It is worth noting that \( \ln K_{Mg} \) increases linearly with 1/T, according to thermodynamic principles of cation partitioning (Fig. 7b). In contrast, partition coefficients measured as the ratio between plagioclase rim and matrix glass show values much higher than those expected for equilibrium crystallization (Fig. 7b), as for the case of \( K_i^{true} > K_i^{app} \) due to the effect of undercooling (Mollo et al., 2011). If the advancing plagioclase rim does not violate the condition of crystallization into an infinite melt reservoir, the value of \( K_i^{true} \) can be modelled as a function of melt and crystal parameters and can be ascribed to rapid plagioclase growth velocities of \( -2 \times 10^{-8} \) cm/s (Fig. 7c).
7b; see also Table 5S for the entire numerical dataset). Decompression-induced crystallization experiments of Brugger and Hammer (2010) have demonstrated that, in calc-alkaline melts, the growth velocity of plagioclase scales with the decomposition path of magma (ΔP). It is found that ~10^-3 MPa/s ΔP corresponds to ~10^-6 cm/s C°. If magma decomposition started at P = 200 MPa (Fig. 5) over a timescale of ~10^-3 MPa/s ΔP, the ascent velocity of magma feeding eruption was ~0.03 m/s (i.e., 100 MPa ≈ 3 km), in agreement with values estimated for a number of volcanic eruptions worldwide (Aloiis et al., 2006; Toramaru et al., 2008; Rutherford, 2008; Gonnermann and Manga, 2013; Mollo et al., 2015).

5.4. Magma genesis and slab inputs

While partial melting of the mantle wedge is the predominant source of magmatism in Central America, the geochemical signature of arc magmas is highly influenced by the nature of the subducted slab components (e.g., Carr et al., 2004). An enriched MORB-like mantle has been identified as the primary source for CAVA magmas with the contribution of fluxes of metasomatic fluids and/or melts produced by the crustal units of the subducting Cocos Plate, i.e. the basal altered MORB unit, the middle carbonate unit, and the upper hemipelagic unit (Patino et al., 2000). A generalized approach for identifying the transfer agents between the subducted slab and the mantle wedge is based on the knowledge that ratios of some specific incompatible elements weakly change over the range of mantle melting and/or during assimilation ± fractional crystallization processes. In contrast, the same incompatible element ratios are greatly affected by the contribution of the subducting slab, being distinctive indicators of sediment input into magma genesis (e.g., Cameron et al., 2002).

Considering the different geochemical signature of the hemipelagic and carbonate sediments subducted beneath Central America, the use of U/La and Ba/Th ratios has the advantage to clearly separate the two slab components (Patino et al., 2000). These ratios correspond to soluble/insoluble element pairs with the important feature that U/La is higher in the hemipelagic sediments and Ba/Th is higher in the carbonate sediments (Fig. 8a). Using partition coefficients from literature and the modal batch melting equation, Cameron et al. (2002) modelled the role played by melts and fluids derived from the subducted slab for the partial melting of the enriched MORB source (Fig. 8a). Modelling results indicate that the majority of primitive magmas at the CAVA have relatively low U/La and Ba/Th ratios and cluster near the enriched MORB source. Ba-rich fluids from the carbonate sediments produce magmas with clear slab-fluid signatures (>0.1%) corresponding to high Ba/Th ratios and low U/La ratios observed in Nicaragua and addressed to an increased dip of the subducting Cocos Plate (Patino et al., 2000). In contrast, as the degree of differentiation proceeds, volcanoes in Costa Rica and El Salvador are weakly influenced by slab-fluid inputs of carbonate origin (Fig. 8a). In El Salvador, Ba/Th and U/La ratios of magmas show a low contribution of melts (<0.04%) from the subducted hemipelagic sediments and a relative high participation of fluids (<2%) from the mature oceanic crust (Fig. 8a).

Additional important information concerning the genesis of Central American magmatism can be retrieved by using ratios of elements that are not highly mobile in arc systems, such as REE and HFSE, in order to better evaluate the role of slab components with melt-like

![Fig. 8. U/La vs. Ba/Th diagram based on soluble/insoluble element pairs. Using these element ratios, Cameron et al. (2002) modelled the role played by melts and fluids (grey trajectories) derived from the subducted slab for the partial melting of the mantle wedge (a). La/Sm vs. Ba/La diagram based on ratios of elements that are not highly mobile in arc systems, such as the REE and HFSE. This diagram allows to evidence the contribution of to the mantle wedge of melt-like components derived from the subducted slab (b). δ18O vs. δ15N diagram that serve to discriminate crustal and source contamination. Cameron and Walker (2006) modelled the mixing trajectories between the sediment-modified mantle (blue trajectory) and crustal contaminants (green trajectory) (c). δ87Sr/86Sr vs. 143Nd/144Nd diagram shows evidence of crustal contamination for rocks in Guatemala that are behind the volcanic front. However, most of the volcanic products in Central America define an array with positive slop that represents a mix between the enriched MORB source and the subducted slab (d). EM, enriched MORB source. OC, oceanic crust. CS, carbonate sediments. HS, hemipelagic sediments. DM, depleted MORB source.](image-url)
properties (Fig. 8b). Volcanic products in Nicaragua form a nearly verti-
cal trend at low La/Sm extending towards the highest Ba/La ratios with
respect to other CAVA magmas (Fig. 8b). Taken together with the dis-
cussion of Ba/Th and U/La ratios, this finding corroborates the addition
to the mantle wedge of variable amounts of Ba-rich fluids derived from
subducted carbonate sediments. Conversely, volcanic products in
Costa Rica are characterized by the highest La/Sm and La/Yb ratios due
to remarkable LREE enrichments (Fig. 8b) but among the lowest Ba/La
and Ba/Th ratios, suggesting either involvement of an enriched mantle
wedge or a melt-like component derived from the subducted slab
(Sadofsky et al., 2007). Volcanic products in El Salvador are interme-
cdiate between the geochemical signature of magmas in Nicaragua and
Costa Rica, being characterized by relative low La/Sm and moderate Ba/La
ratios due to pronounced slab-fluid signals from marine sedi-
ments (Fig. 8b).

For discriminating between crustal and source contamination of
CAVA magmas, Cameron and Walker (2006) modelled the oxygen and
strontium isotopes in order to define mixing trajectories between the
sediment-modified mantle and crustal end-members (Fig. 8c). For
most rocks in Guatemala produced by back-arc volcanism behind the
volcanic front, there is clear evidence of crustal contamination (>25%).
This accounts for the increased continental crust thickness and the high-
ly radiogenic nature of the old crust (cf. Carr et al., 1990; Walker et al.,
1995). In contrast, in Central America, crustal assimilation causes
weak changes in the geochemical characteristics of magmas (Fig. 8c).
This is particularly true for volcanoes in El Salvador, Nicaragua, and
Costa Rica, emplaced in a thin and young continental crust (cf. Eiler et
al., 2005) and characterized by magmatism with source contamination
signature (<5%).

Sr and Nd systematics presented by Cameron et al. (2002) confirm
that magmas in Guatemala extend in the direction of high degrees of
crust contamination (Fig. 8d). On the other hand, volcanic products in
El Salvador, Nicaragua, and Costa Rica define an array with positive slope
(Fig. 8d) as the result of a mix between an enriched MORB source and
the subducted slab (Feigenson and Carr, 1986; Carr et al., 1990).
The slab source itself represents a mix between a depleted MORB source and
sediments plus altered basaltic crust (Fig. 8d). Boron isotope data by
Taronir et al. (2007) for El Salvador products acknowledge the impor-
tance of slab-derived aqueous fluids as metasomatizing agents of the
mantle wedge. These aqueous fluids are mostly produced by dehydra-
tion of marine sediments and altered basaltic crust of the subducted
mantle wedge or a melt-like component derived from the subducted slab
(Sadofsky et al., 2007). Boron isotope data by

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6. Conclusions

This study documents for the first time the mineralogical, petrolog-
ical and geochemical characteristics of products erupted during the
2013 eruption of Chaparrastique volcano. Mineral-melt equilibria and
bulk rock modelling indicate that the eruption was likely triggered by
the input of hotter, basaltic magma from depth into a colder, basaltic an-
desitic reservoir residing at shallow crustal levels. Magma mixing is sup-
ported by the textural and compositional characteristics of olivine and
titanomagnetite reflecting different crystallization histories, as well as
by the occurrence of inversely zoned plagioclases showing partly re-
sorbed cores surrounded by sieve-textured mantles. Furthermore, the
final growth of plagioclase was controlled by the effect of undercooling
due to rapid decompression during magma ascent to the surface. Trace
element and isotope data tend to exclude crustal contamination, sug-
gesting that magmas originated by partial melting of an enriched MORB-like mantle wedge metasomatized prevalently by slab-derived
aqueous fluids.

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