Open-system processes in the differentiation of mafic magma in the Teide–Pico Viejo succession, Tenerife

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Abstract: Oceanic island basalts are commonly thought to differentiate by fractional crystallization, yet closed-system fractionation models have so far failed to reproduce major and trace element variations observed in mafic lavas from the Teide–Pico Viejo stratovolcano complex on Tenerife. Here, new high-precision plagioclase trace element data are fed into such a fractionation model. The results confirm that fractionation of phenocrysts found in the lavas does not reproduce trace element variations, in particular enrichment of Sr and Zr observed in the Teide–Pico Viejo mafic suite. This enrichment of Sr and Zr is tested by an energy-constrained recharge, assimilation and fractional crystallization (EC-RAFC) model at high $T$ and low $\Delta T$ intervals, consistent with previously determined magma storage beneath Tenerife at sub-Moho depths. Published mineral–melt equilibrium relations using the plagioclase anorthite content ($0.4 < X_{An} < 0.8$) constrain the temperature during differentiation. Gabbroic xenoliths found in Tenerife lavas are assumed as contaminant. Enrichment of Sr and Zr in the Teide mafic suite is reproduced by this combined assimilation and fractional crystallization model, as assimilation causes higher degrees of enrichment in incompatible trace elements than is possible by crystal fractionation alone. Recycling of plutonic roots may thus have significantly enriched trace elements in the primitive lavas of the Teide–Pico Viejo succession.

Supplementary material: Detailed average mineral compositions of low and high Sr–Zr lavas, composition of the bulk extracts and full graphs of the recalculated closed-system model are available at www.geolsoc.org.uk/SUP18604.

The role of open-system processes in the petrogenesis of oceanic island volcanic suites has been controversial (Davidson & Bohrson 1998). The fundamental problem is the compositional similarity of oceanic crust and mantle-derived basaltic magma; consequently, signs of crustal assimilation are subtle and hard to detect. The Teide–Pico Viejo succession in Tenerife, Canary Islands contains abundant mafic lavas with compositions that are in disequilibrium with mantle olivine. This implies pre-eruptive differentiation of mafic magmas, which has been modelled by closed-system fractional crystallization (Ablay et al. 1998). Up to now, the Teide–Pico Viejo complex has mainly been studied as a prime example for the formation of felsic magma in ocean islands (Ridley 1970; Araña et al. 1989; Albert-Beltrán et al. 1990; Ablay et al. 1998; Carracedo et al. 2007; Wiesmaier et al. 2012). Recently, the radiogenic isotope signatures of the basanite–phonolite sequence at Teide have been found to be strongly affected by open-system processes, including assimilation of pre-Teide island core material (Wiesmaier et al. 2012). This invites the question of whether more mafic magmas at Teide–Pico Viejo are also the products of assimilation and magma mixing. As a result, analyses of radiogenic isotopes are insufficient for constraining the differentiation processes that gave rise to Teide–Pico Viejo mafic compositions. The focus of this study is therefore to compare open- and closed-system models based on major and trace element concentrations, including appropriate compositions for a potential contaminant.

This revision of the previous model of differentiation is based on three factors. First of all, high-precision plagioclase trace element data from the Teide–Pico Viejo succession are now available (Wiesmaier 2010). These data allow refinement of the closed-system model presented for Teide by Ablay et al. (1998). For example, in mafic liquids, plagioclase is the main phase that incorporates Sr. This trace element may thus serve as a tracer of magmatic differentiation in Teide mafic lavas, which previously could not be determined owing to lack of in situ trace element data. Furthermore, the calculated bulk partition coefficients for Sr are now more reliable, because they are based on measured in situ data.

Second, empirical equations on the relationship of anorthite content in plagioclase and temperature of crystallization allow the thermal conditions in a magma reservoir during crystallization of plagioclase to be constrained (e.g. Blundy & Wood 1991; Bindeman et al. 1998; Bindeman & Bailey 1999; Bédard 2006; Namur et al. 2012). The wide stability field of feldspar (equivalent to 0–25 km depth in the crust; Borghini et al. 2009, and references therein), its ability to crystallize from a wide variety of melt compositions and its sustained ‘resistance’ to diffusional re-equilibration of major elements (e.g. Morse 1984) imply that plagioclase data are a robust means of reconstruction of some of the intensive parameters that affected crystallization (see Namur et al. 2012, and references therein).

Finally, an energy-constrained recharge, assimilation and fractional crystallization (EC-RAFC) model (Spera & Bohrson 2001) is calculated to investigate the thermal and compositional evolution...
of Tenerife mafic magma at depth. The new plagioclase data, along with the revised bulk partition coefficients, and the thermal constraints from the empirical equations on anorthite content are fed into the EC-RAFC model. This combination of thermodynamic and compositional parameters embedded in a framework of realistic thermal conditions ensures a rigorous approach to evaluating whether or not open-system processes may be at work in the petrogenesis of mafic lavas of the Teide–Pico Viejo sequence.

This study therefore focuses on lavas of the Teide–Pico Viejo succession with SiO₂ <53 wt%. First, the closed-system model is tested by updating the approach of Ablay et al. (1998) with new high-precision microanalytical data from a large number of plagioclase crystals for their major and trace element compositions (Wiesmaier 2010) and whole-rock major and trace element data from Rodríguez-Badiola et al. (2006). Then, the temperature of plagioclase crystallization is reversely modelled using the empirical relationships from the literature. Finally, plagioclase data, bulk partition coefficients derived from the closed-system model and temperature information are fed into an EC-RAFC model to test for a combination of assimilation and magma mixing during continuing fractional crystallization.

Geology of Tenerife

The overall structure of Tenerife is controlled by a three-armed rift zone system (Fig. 1). The three arms to the NW, NE and south join beneath Teide–Pico Viejo volcano. Proto-rifts may have already been active as early as Miocene times (Carracedo et al. 2011). The NW and NE arms of this system are volcanically active and extend into the peripheral shield volcanoes Teno and Anaga (Carracedo 1994). The rifts show mainly mafic volcanism (basanite to phonotephrite) originating from single or multiple (and often aligned) monogenetic cones. Mineral assemblages are restricted to olivine, augite, Fe–Ti oxides and in some cases plagioclase.
Prior to the formation of the central Teide complex, a giant landslide incised the central Las Cañadas volcano complex at c. 200–180 ka, at the junction of the three rift zones, to leave behind the Icod collapse scar (Watts & Masson 1995; Carracedo 1994; Carracedo et al. 2007; Márquez et al. 2008). Pre-existing vertical collapse structures probably contributed to the lateral instability of Las Cañadas volcano (e.g. Martí et al. 1994, 1997; Troll et al. 2002). The Icod landslide unroofed the triple junction of the rift zone (see Márquez et al. 2008) and initiated the construction of proto-Teide inside this collapse embayment.

The Teide–Pico Viejo succession is the youngest eruptive sequence of Tenerife and consists of the central Teide–Pico Viejo complex, the monogenetic vents located around Teide–Pico Viejo, and vents of the NW and NE rift zones that are contemporaneous with the Teide–Pico Viejo complex (Carracedo et al. 2007).

Initial eruptions at Teide–Pico Viejo produced mafic lavas indistinguishable from rift zone eruptions (Carracedo et al. 2007). Between 30 and 20 ka, the Teide–Pico Viejo edifice and its flank vents began to erupt more differentiated material, producing exclusively phonolite during the last 20 kyr (Carracedo et al. 2007). The phonolites show significant contamination by a radiogenic Sr island edifice component, most probably at shallow depths (Wiesmaier et al. 2012). This evolution probably resulted from the establishment of a shallow magmatic plumbing system underneath the progressively growing central complex. The rift zones continued to erupt mafic compositions, sampling deeper sub-Moho to intermediate oceanic crust reservoirs. The interaction between these two regimes, rift zone and central volcano, is shown in the boundary zone between them, where mixing of rift zone basanite and central complex phonolite magmas has occurred (Araña et al. 1994; Wiesmaier et al. 2011). This study exclusively focuses on the mafic lavas erupted in the Teide–Pico Viejo succession. The samples therefore comprise rocks from the initial eruptions of Teide–Pico Viejo along with a large number of samples from the currently active rift zones.

Previous work on the Teide–Pico Viejo succession

The closed-system model of Ablay et al. (1998)

Ablay et al. (1998) proposed a model of closed-system fractional crystallization for Teide–Pico Viejo lavas on the basis of analysed major element mineral compositions and a multiple-step mass-balance calculation with a least-squares regression analysis for every modelled step. Trace elements were modelled using whole-rock concentrations and partition coefficients from the literature. In situ trace element data from minerals were not available, however. Whereas major element trends were successfully modelled, trace element concentrations of the daughter compositions were inconsistent with those found in nature. The calculated residual liquids for the most mafic compositions (models A–D) showed discrepancies of tens of per cent for several trace elements, regardless of whether an element was compatible or incompatible. For instance, the Sr concentration of model A had a 27% deviation from the targeted daughter composition. In those cases where Sr appeared to be consistent with the model, other elements showed strong discrepancies. Ablay et al. (1998) therefore invoked selective addition of zoisite and hydrothermally altered facies, although these end-members and the contamination mechanism were not specified any further. In such a scenario, however, the oxygen isotope ratios of mafic lavas ought to display δ18O values significantly displaced from normal magmatic ratios (Donoghue et al. 2008), which cannot be confirmed (Wiesmaier et al. 2012).

Also with respect to the most mafic lavas of the sequence, for which contamination by a shallow component has been ruled out (Wiesmaier et al. 2012), the trace element models of Ablay et al. (1998) fail to reproduce natural compositions. Nevertheless, low Mg-numbers and disequilibrium with mantle olivine for even the most mafic products of the Teide–Pico Viejo complex (e.g. Ablay et al. 1998) require some magmatic differentiation.

Thermobarometric studies

Current knowledge of Teide’s plumbing system places constraints on conditions for differentiation of mafic magmas. Magma ascent at Teide is controlled by a rift zone system that probably lacks interposed magma chambers (Carracedo 1994, 1996), and is thus considered rapid. Thermobarometric studies suggested that mafic magmas of the Canaries differentiated at upper mantle and lower crustal levels (Ablay et al. 1998; Hansteen et al. 1998; Klügel et al. 2000, 2005; Galipp et al. 2006; Longpré et al. 2008; Stroncik et al. 2009). The recent submarine rift zone eruption on the western island of El Hierro is a case in point. Consistent with thermobarometry, magma movement was seismically traced at sub-Moho depths for almost three months. A few days before the onset of the eruption, the seismic activity migrated towards the surface, indicating a fast ascent of magma through the oceanic crust and the island edifice (López et al. 2012). As a result, shallow, felsic contaminants can be excluded for these magmas, consistent with their monotonous Sr isotope ratios and Nd and Pb isotope ratios that are in line with mantle source variations (Wiesmaier et al. 2012). Because of the similar storage conditions for mafic magmas detected in different islands of the Canaries, Teide mafic lavas must have undergone very similar P–T histories.

Geochemistry of the Teide–Pico Viejo succession

In a partner study to the stratigraphic revision of the Teide–Pico Viejo succession by Carracedo et al. (2007), the entire succession has been analysed for major and trace elements (Rodríguez-Badiola et al. 2006). Both stratigraphy and geochemical data are a critical addition to the previously published closed-system model by recognizing more eruptions as part of the Teide–Pico Viejo succession than Ablay et al. (1998). The mafic lavas of the Teide–Pico Viejo succession (here regarded as having <53 wt% SiO2) are separated into two groups, one with low Sr and low Zr concentration (<350 and <1000 ppm, respectively) and the other with high Sr and high Zr concentration (>300 and >1000 ppm, respectively; Fig. 2). The two groups, low Sr–Zr and high Sr–Zr, cannot be distinguished systematically by incompatible trace element ratios or other geochemical parameters, although the high Sr–Zr lavas tend to be the more evolved. The inconsistencies in trace element concentrations that the Ablay et al. (1998) fractionation models showed for the Teide–Pico Viejo succession are thus exemplified by Sr and Zr.

Plagioclase possesses high melt–mineral partition coefficients for Sr (Blundy & Wood 1991) and is thus especially suitable as a tracer of differentiation from low Sr–Zr to high Sr–Zr mafic lavas that are present at Teide. Strontium is incompatible in olivine and considerably less compatible in the phases of interest (amphibole and clinopyroxene) than it is in plagioclase. It is therefore possible to monitor magmatic processes that occur within the feldspar stability field by means of Sr concentration data from feldspar. Using Zr, in turn, provides a measure of the degree of differentiation that is independent of any of the phases that potentially fractionate in the mafic regime, as Zr is incompatible in the alkaline series up to felsic compositions (Watson & Harrison 1983; Wolff & Toney 1993). Because Sr and Zr are both enriched with degree of differentiation in the Teide–Pico Viejo mafic lavas, an initial hypothesis may be the incompatible behaviour of Sr in absence of plagioclase.
This explanation is offset, however, by the presence of plagioclase in some of the lavas of both groups, so that Sr enrichment and absence of plagioclase do not correlate (see Fig. 2).

Methods

Feldspar microanalysis

Feldspars of the Teide–Pico Viejo succession have been analysed for major and trace element concentrations in single zones of each crystal. Major element analyses were performed with a Cameca SX-50 and trace element analyses using a New Wave™ UP-213 Nd:YAG laser ablation unit that was coupled to a ThermoFinnigan Element2™ inductively coupled plasma mass spectrometer. Both types of measurements were carried out at the GeoAnalytical Laboratory of Washington State University, USA. Details of the method have been provided by Olin & Wolff (2010) and Wiesmaier (2010). Compositions representative of the feldspar crystals found in Teide mafic lavas are given in Table 1.

Closed-system modelling

A revised fractional crystallization model for Teide mafic lavas is presented. The input parameters and the conceptual approach represent the framework of the model and are thus outlined in more detail. The ‘multiple-step’ strategy of Ablay et al. (1998) was adopted, using a least-squares regression analysis and a mass-balance calculation for every modelled step. Rayleigh fractionation has been assumed. Regarding the narrow range of SiO₂ concentrations (<53 wt%), two steps were calculated, similar to the Ablay et al. (1998) approach. The first model step is calculated to simulate evolution from the most mafic, low Sr–Zr lava towards the high Sr–Zr group. The second step models the variation across the high Sr–Zr group (Fig. 3).

Whole-rock Fe₂O₃ data have been recalculated to Fe₂O₃ and Fe using an Fe²⁺/Fe³⁺ ratio of 2.16, which was measured for Teide basanite (Ridley 1970). Whole-rock oxides were normalized to 100% on a water-free basis. All other major element mineral data are from Ablay (1997), and the minor oxides SrO and BaO from that source have been recalculated to ppm. Clinopyroxene mineral data have been complemented by average Sr and Zr trace element concentrations in clinopyroxene from a Las Cañadas basanite (sample TF58 with 44 wt% silica; Neumann et al. 1999). Of the 10 phenocryst phases identified in the entire Teide–Pico Viejo succession, six are present in the mafic lavas: olivine (ol), clinopyroxene (cpx), plagioclase (plag), apatite (ap), titano-magnetite (mt) and ilmenite (ilm) (Ablay et al. 1998). This fractionation assemblage is varied according to the least-squares regression calculation and with plagioclase being included or not depending on the phase assemblage of the respective parent composition.

Average feldspar compositions of low and high Sr–Zr lavas are from Wiesmaier (2010) and the major element data for the remaining minerals have been given by Ablay (1997). A representative set of feldspar data is shown in Table 1. In summary, mineral compositions in the low Sr–Zr group are Fo₇₉–₈₄ (ol), Wo₃₈–₄₃ En₄₆–₅₁ Fs₈–₁₁ (cpx), An₇₃–₈₄ (plag), Usp₄₃–₇₀ (mt) and Ilm₈₇–₉₄ (ilm). Apatites occur as inclusions in cpx and are mostly hydroxy-fluorapatites. Mineral compositions in the high Sr–Zr group are of low variability and have thus been averaged to achieve a bulk extract. Mineral compositions in the high Sr–Zr group are Fo₇₉–₈₄ (ol), Wo₃₈–₄₃ En₄₂–₅₁ Fs₈–₁₁ (cpx), An₇₃–₈₄ (plag), Usp₄₃–₇₀ (mt) and Ilm₈₅–₉₄ (ilm) and, similar to the low Sr–Zr group, apatites occur as inclusions in cpx and are hydroxy-fluorapatites. The composition of this bulk extract varies across the 16 calculated models depending on the respective least-squares regression coefficients.
Differences in deformation of feldspar from low and high Sr–Zr lavas of Teide–Pico Viejo

Table 1. Representative selection of analyses of feldspar from low and high Sr–Zr lavas of Teide–Pico Viejo

| Sample          | Low Sr–Zr lavas | High Sr–Zr lavas |
|-----------------|-----------------|------------------|
|                 | CA1-75-1-01-r   | CA1-75-1-12-c    |
| Distance from core (µm): | 1900 | 0 |
| EMP (wt%)       | 46.09 45.39 48.51 | 58.49 60.75 55.34 |
| SiO₂            | 46.09 45.39 48.51 | 58.49 60.75 55.34 |
| Al₂O₃           | 33.34 34.35 32.34 | 25.57 23.41 26.58 |
| Fe₂O₃           | 0.68 0.80 0.86 0.46 0.57 0.46 |
| K₂O             | 0.29 0.20 0.19 0.85 1.04 0.53 |
| Na₂O            | 1.95 1.61 2.78 7.18 7.76 5.97 |
| CaO             | 15.73 16.78 15.14 6.64 5.06 8.71 |
| BaO             | 0.01 0.00 0.00 0.14 0.37 0.02 |
| Total           | 98.10 99.13 99.83 99.34 98.96 97.62 |
| An (mol%)       | 80.23 84.19 74.22 32.16 24.88 43.23 |
| Ab              | 18.00 14.59 24.70 62.91 69.03 53.63 |
| Or              | 1.78 1.22 1.08 4.92 6.10 3.14 |
| LA-ICP-MS (ppm) | Rb 0 2 1 2 | |
|                  | Ba 169 136 102 209 1232 850 1020 |
|                  | La 6 5 3 4 17 13 10 |
|                  | Ce 10 8 5 5 20 18 13 |
|                  | Pr 1 1 -- 1 1 1 |
|                  | Nd 3 2 2 2 3 3 2 |
|                  | Eu 1 1 -- 2 1 1 |
|                  | Y -- -- -- -- -- -- |
|                  | Pb -- 1 -- 3 3 3 |
|                  | Sr 2703 2642 1944 2106 2578 3350 3050 |
|                  | Ti 481 461 510 855 634 680 500 |
|                  | Mg 551 584 630 879 155 241 247 |

The complete dataset of the Teide–Pico Viejo succession comprises 785 electron microprobe (EMP) and 766 laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) data points; details on the method have been given by Wiesmaier (2010). Hyphens in trace element data denote values below 0.4 ppm that have been rounded down to zero.

Fig. 3. SiO₂ v. MgO of the low and high Sr–Zr lava samples, the bulk extract compositions from the calculated closed-system model, and Tenerife cumulate xenolith compositions from Neumann et al. (1999). Step 1 describes the evolution from the most primitive low Sr–Zr composition to the high Sr–Zr lavas and step 2 designates the variation within the high Sr–Zr lava compositions.

Strontium is compatible in plagioclase, making plagioclase the key mineral for mass-balance models that include Sr concentrations. The new high-precision feldspar data provided by Wiesmaier (2010) thus guarantee a more realistic estimation of the Sr contents of the fractionated assemblage. Throughout the two-step model, the presence of plagioclase was systematically varied and four permutations were calculated: (parent + plag)/(daughter + plag), (parent + plag)/(daughter − plag), (parent − plag)/(daughter + plag), (parent − plag)/(daughter − plag). For each of these permutations, four eligible parent/daughter pairs were selected, accounting for a total of 16 calculated fractionation models. This strategy allowed evaluation of the compositional effects that fractional crystallization may exert on the natural parent compositions at a high resolution.

Determination of melt compositions and crystallization temperatures

Empirical relationships have been employed to constrain the crystallization temperature of plagioclase, which is an essential input parameter for the subsequently presented EC-RAFC model. Several studies have quantified elemental plagioclase–melt partitioning based on synthetic and natural examples (Blundy & Wood 1991; Bindeman et al. 1998; Bédard 2006). Namur et al. (2012) revised the empirical relations for plagioclase–melt equilibria, using a database of results from 1 atm anhydrous experiments. However, their regression models are tied to more than one compositional parameter, for which reason they do no lend themselves to a reverse modelling approach, despite the accuracy of their model being superior in forward modelling.
In turn, the empirical relationships of Bindeman et al. (1998) and Bédard (2006) allow a reconstruction of key parameters for subsequent modelling of magmatic differentiation. Based on pre-existing natural and experimental data, Bédard (2006) developed several empirical equations that relate the anorthite content of plagioclase to the MgO concentrations of the melt from which the analysed plagioclase compositions crystallized:

$$\ln(\text{MgO}) = \frac{X_{\text{An}} - (b \pm \Delta b)}{a \pm \Delta a}$$

(1)

where $a$ is the slope of the calculated regression and $b$ is the intercept of the regression on the $y$-axis. The bivariant nature of the equations permits reverse modelling of various chemical and physical parameters of the parent melt of the analysed Teide–Pico Viejo plagioclase crystals. In a second step, the temperature at which a given zone of feldspar crystallized may be calculated from the previously calculated MgO composition of the melt:

$$\frac{10000}{T} = a \ln(\text{MgO}) + b.$$  

(2)

All parameters used for each modelling step are listed in Table 2.

**EC-RAFC starting point: justification of input parameters**

An EC-RAFC model is presented, which requires a wide variety of input parameters such as crystallization or fusion enthalpies, magma and contaminant temperature and composition. These parameters are justified in the methods section to separate them from results and subsequent interpretation. The theoretical background to the EC-RAFC model has been laid out by Spera & Bohrson (2001, 2002, 2004) and models of natural systems were presented by Bohrson & Spera (2001, 2003) and (Fowler et al. 2004). All input parameters for the EC-RAFC model are summarized in Table 3.

**Envisaged scenario.** In the EC-RAFC model presented here, a batch of mafic magma is in thermal and compositional equilibrium with the cumulate rock that precipitated from the magma earlier on. Recharge with a new batch of superliquids, low Sr–Zr magma (hereafter referred to as ‘recharge magma’) induces thermal and compositional disequilibrium and subsequent equilibration. The hotter recharge magma thus induces anatexis in the cumulate. Subsequently, the reservoir cools again, and fractionation resumes production of cumulate. It is tested whether or not this scenario is able to reproduce the composition of a high Sr–Zr magma.

**Temperature constraints.** Owing to the constant heat flow from mantle to crust, the temperature fluctuations at Moho depth will be small and the cumulate rock is probably kept at near-solidus temperatures, reducing the $\Delta T$ necessary to initiate anatexis. Hydrothermal cells would not be expected at Moho depth, for which reason an isenthalpic AFC scenario is assumed (see Reiners et al. 1995). As a consequence, we assume a narrow temperature interval of $\Delta T = 23$ K for the EC-RAFC scenario between the temperature of the hot recharge magma and thermal equilibration.

A temperature of 1300°C was assigned to the liquidus and as the initial temperature of the recharge magma. Pristine magma temperature was assumed to be 1290°C ($T_l^0 = T_m^0$), consistent with thermobarometric constraints (Ablay et al. 1998) and the results from anorthite temperature modelling presented here. The difference of −10 K to the recharge magma provides an increase in thermal energy upon recharge. The equilibration temperature has been set to 1277°C; that is, below the initial temperature of pristine magma to trigger crystallization and above the cumulate’s solidus to allow anatexis in the cumulate. The solidus temperature $T_s$ has been set to 1250°C to yield small degrees of partial melt from the gabbroic cumulate (Table 3). Long-term magma chamber replenishment should balance with intermittent expulsion of magma. Hence, the thermal parameters were set to even out the mass of anatetic melt and cumulate that is produced (so as not to clog the magma chamber or remelt all the cumulate).

**Composition of magma and cumulate.** The Sr, Nd, Zr and Ni concentrations of the initial and the recharge magma have been calculated as the average of composition of the low Sr–Zr lavas (data from Rodriguez-Badiola et al. 2006). As contaminant, we assume gabbroic and kaersutite-bearing cumulate rock, which has been found as xenoliths in Tenerife mafic magmas (Neumann et al. 2000). These cumulates have been interpreted to form by fractional crystallization of mafic alkaline magma at depth and thus represent a potential end-member for assimilation during recharge. The average composition of these analysed cumulate samples has been used as contaminant data in the model (Table 3).

**Partition coefficients.** The trace elements Sr and Zr were modelled together with Nd and Ni, the latter two as a control for REE behaviour and compatible elements. To ensure comparability between the EC-RAFC and the closed-system model, the same

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### Table 2. Parameters used for melt modelling equations

| $Y$ | $X$ | $a$ | $\pm a$ | $b$ | $\pm b$ | Comment | Reference | Reference equation number |
|-----|-----|-----|---------|-----|---------|---------|-----------|--------------------------|
| Melt MgO (wt%) | | | | | | | | |
| ln(MgO) | $X_{\text{An}}$ | 0.04448 | ±0.00158 | 0.42132 | ±0.07065 | For dry melts, MgO > 1 wt% | Bédard 2006 | 3a |
| ln(MgO) | $X_{\text{An}}$ | 0.50206 | ±0.09061 | 0.10090 | ±0.10362 | For dry melts, MgO > 1 wt% | Bédard 2006 | 3b |
| ln(MgO) | $X_{\text{An}}$ | 0.10639 | ±0.00444 | 0.57229 | ±0.13285 | Wet melts | Bédard 2006 | 3c |

| Crystallization temperature (°C) | | | | | | | | |
| 10000/T | ln(MgO) | −0.95668 | ±0.01728 | 10.3758 | ±0.0232 | Bédard 2006 | 5a |
| 1/T | ln(MgO) | −2.04 × 10−4 | 7.92 × 10−4 | Bindeman et al. 1998 | 3 |

All calculations follow the equation $Y = aX + b$. 
bulk partition coefficients as calculated in the closed-system model were employed. These were computed using the trace element data from plagioclase, partition coefficients from the literature for Nd and Ni concentrations in olivine, magnetite, ilmenite andapatite (Fujimaki 1986; Nielsen 1992; Ewart & Griffin 1994; Zack & Brumm 1998; Adam & Green 2006), and analysed olivine and clinopyroxene compositions from Tenerife basanites (Neumann et al. 1999). Bulk partition coefficients calculated from the closed-system models yielded the following ranges: Sr 0.13–0.89 (average 0.5) and Zr 0.18–0.60 (average 0.41). Furthermore, bulk partition coefficients for Nd and Ni were calculated to serve as input parameters for the EC-RAFC model; Nd yielded 0.5–3.10 (average 1.20), and Ni 4.0–12.6 (average 8.0). The bulk partition coefficients employed in the EC-RAFC model are consistent with the ranges of bulk $D$ values shown here (Table 3).

**Thermodynamic parameters.** All end-member compositions and their fusion and crystallization enthalpies are constrained by natural data. Specific heat capacities and crystallization or fusion enthalpies were calculated from the oxide and mineral data given by Neumann et al. (2000). We assumed mineral percentages of 30% plagioclase, 30% kaersutite, 20% clinopyroxene and 15% oxides plus 5% minor phases as typical compositions of a Tenerife gabbroic cumulate. The recalculated closed-system model

**Inherent EC-RAFC parameters.** In mantle and cumulate xenoliths, interstitial melt is frequently found, which implies that melt extraction is usually incomplete. The normalized fraction of anatectic melt extracted from the contaminant ($\gamma$) was thus assumed to be 0.95. The relative mass of recharge $M_r$ is kept at 0.5 to simulate a batch of recharge magma smaller than the total volume of the magma reservoir. Partition coefficients were kept constant throughout the model, as a relatively small compositional window of differentiation is simulated ($\Delta SiO_2 = 3 wt\%$).

### Results

**Modelling step 1: low Sr–Zr to high Sr–Zr compositions.** Three combinations of parent–daughter lava compositions have been calculated for each of the four scenarios, giving 12 models in total for step 1. Bulk extracts resembled the compositions of gabbroic xenoliths from Tenerife (see Neumann et al. 1999; Fig. 3). Examples of $F$ values, bulk extract compositions and bulk partition coefficients of scenario 1 are shown in Table 4.

**Scenario 1: both parent and daughter bear feldspar.** An overall good fit for major elements was achieved. Exceptions were TiO$_2$ and MnO, which were underestimated by −14 to −16% and −17 to −19%, respectively. Trace elements Zr and Sr were underestimated by −2 to −4% and −5 to −17%, respectively.

**Scenario 2: both parent and daughter are feldspar-free.** Of the major elements, TiO$_2$ was underestimated by −12 to −15% and CaO by −6 to −9%. $K_2O$ varied by +3 to −11%. Al$_2$O$_3$ and FeO were overestimated by +6 to +9% and MgO varied from −11% to +14%. Strontium deviated variably by zero to −18% and Zr was underestimated by −15 to −20%.

**Scenario 3: parent bears feldspar and daughter is feldspar-free.** Silica was overestimated by +1%, translating to c. +0.5 wt% difference. Al$_2$O$_3$ was underestimated by zero to −11%, whereas Fe$_2$O$_3$ and FeO were overestimated by +6 to +16% and +4 to +12%, respectively. Strontium was underestimated by −18 to −22% and Zr by −1 to −6%.

**Scenario 4: parent is feldspar-free and daughter bears feldspar.** This is the scenario with the overall highest variability in major elements. TiO$_2$, MnO, Na$_2$O, K$_2$O and P$_2$O$_5$ were underestimated by more than −15%, whereas Al$_2$O$_3$, Fe$_2$O$_3$ and FeO either fitted well or were overestimated by more than +10%. Strontium was underestimated by

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**Table 3. Parameters for EC-RAFC modelling**

| Parameter                      | Value       |
|--------------------------------|-------------|
| Thermal parameters             |             |
| Pristine magma initial temperature, $T_m$ | 1290°C      |
| Recharge magma initial temperature, $T_m$ | 1290°C      |
| Assimilant initial temperature, $T_a$ | 1210°C      |
| Recharge $M_r$ $°C$            | 0.5         |
| Crystallization enthalpy, $\Delta_h$ (J kg$^{-1}$ K$^{-1}$) | 1479        |
| Isobaric specific heat of magma, $C_{pm}$ (J kg$^{-1}$ K$^{-1}$) | 1307        |
| Fusion enthalpy, $\Delta_h$ (J kg$^{-1}$) | 364000      |

| Compositional parameters       |             |
|--------------------------------|-------------|
| Pristine magma initial concentration (ppm), $C_m$ | 861         |
| Pristine magma trace element distribution coefficient, $D_m$ | 0.89        |
| Recharge magma initial concentration (ppm), $C_r$ | 861         |
| Recharge magma trace element distribution coefficient, $D_r$ | 0.89        |
| Assimilant initial concentration (ppm), $C_a$ | 1754        |
| Assimilant trace element distribution coefficient, $D_a$ | 0.89        |
| Average concentration of high-Sr/high-Zr magma (ppm) | 1086        |
| Sr                             | 861         |
| Nd                             | 861         |
| Zr                             | 861         |
| Ni                             | 861         |

Melt functions were non-linear, and non-linear logistical parameters were $a = 450$, $b = 11$ for pristine and recharge magma, and $a = 400$, $b = 11$ for the contaminant. 

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Modelling step 2: differentiation within the high Sr–Zr group. One parent–daughter combination has been calculated for each of the four scenarios, which makes four models in total for step 2. An example of data for scenario 1 is given in Table 3.

**Scenario 1**: both parent and daughter bear feldspar. Stringently applying the criterion of lowest average least squares caused SiO$_2$ to be underestimated by −4%. TiO$_2$, MgO, Fe$_2$O$_3$, and FeO were within ±1% of the natural daughter composition, whereas the remaining oxides showed deviations between 4 and 36%. Strontium was overestimated by +30% and Zr underestimated by −17%.

**Scenario 2**: both parent and daughter are feldspar-free. SiO$_2$, TiO$_2$, Al$_2$O$_3$, Fe$_2$O$_3$, FeO, MnO and P$_2$O$_5$ were well reproduced, whereas the remaining oxides showed deviations between 6 and 76%. Strontium was overestimated by +34% and Zr underestimated by −36%.

**Scenario 3**: parent bears feldspar and daughter is feldspar-free. SiO$_2$ was underestimated by −3%. TiO$_2$, Fe$_2$O$_3$, FeO, MgO and CaO were well reproduced, whereas Al$_2$O$_3$, MnO, CaO, K$_2$O, Na$_2$O and P$_2$O$_5$ showed deviations between 6 and 23%. Strontium was underestimated by +34% and Zr overestimated by +2%. MgO, CaO, K$_2$O and Na$_2$O showed deviations between 6 and 23%. Strontium was overestimated by +17% and Zr underestimated by −30%.

**Scenario 4**: parent is feldspar-free and daughter bears feldspar. SiO$_2$ was underestimated by −3%. TiO$_2$, Fe$_2$O$_3$, FeO, MgO and CaO were well reproduced, whereas Al$_2$O$_3$, MnO, CaO, K$_2$O, Na$_2$O and P$_2$O$_5$ showed deviations between 6 and 23%. Strontium was overestimated by +34% and Zr underestimated by −30%.

Throughout the differentiation of mafic magma, Sr appears to be incompatible in bulk owing to the predominant fractionation of non-Sr incorporating minerals (ol, cpx, mt). An enrichment of Sr along with Zr can thus be achieved in principle, but in 14 out of 16 models Sr is not enriched to the degree necessary to reproduce natural daughter compositions. This incompatible behaviour is reflected in the bulk partition coefficients that were calculated for Sr and Zr (Table 4).

**Table 4.** F values, bulk extract compositions and bulk partition coefficients of selected trace elements for scenario 1 of the closed-system model

| Model | Parent: Montaña Cascajo, phase 1 TFC-249 | Daughter: Montaña Reventada basanite TFC-243 | Parent: Montaña Cascajo, phase 3 TFC-287 | Daughter: Montaña Reventada basanite TFC-243 | Parent: Montañas Negras TFC-276 | Daughter: Montaña Reventada basanite TFC-243 | Parent: Montaña Reventada basanite TFC-243 | Daughter: Montaña Reventada basanite TFC-243 |
|-------|----------------------------------------|-----------------------------------------------|----------------------------------------|-----------------------------------------------|----------------------------------------|-----------------------------------------------|----------------------------------------|-----------------------------------------------|
|       | B                                      | C                                             | D                                      |                                               |                                      |                                              |                                               |                                      |
| Model | A                                      |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | Montaña de Chío TFC-540                 |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | Bulk F (%)                             |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | 39.73                                  | 37.78                                         | 48.82                                  | 33.68                                         |                                      |                                              |                                               |                                      |
|       | ol (low Sr–Zr)                         |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | 5.29                                   | 3.87                                          | 1.71                                   |                                               |                                      |                                              |                                               |                                      |
|       | cpx (low Sr–Zr)                        |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | 19.11                                  | 18.11                                         | 23.74                                  |                                               |                                      |                                              |                                               |                                      |
|       | plag (low Sr–Zr)                       |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | 8.00                                   | 8.36                                          | 14.10                                  |                                               |                                      |                                              |                                               |                                      |
|       | ol (high Sr–Zr)                        |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | 2.05                                   |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | cpx (high Sr–Zr)                       |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | 14.15                                  |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | plag (high Sr–Zr)                      |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | 10.12                                  |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | mt                                     |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | 7.29                                   | 7.44                                          | 9.27                                   |                                               |                                      |                                              |                                               |                                      |
|       | il                                      |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | 0.00                                   | 0.00                                          | 0.00                                   |                                               |                                      |                                              |                                               |                                      |
|       | ap                                      |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | 0.04                                   | 0.01                                          | 0.00                                   |                                               |                                      |                                              |                                               |                                      |
|       | **Bulk extract composition (wt%)**     |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | SiO$_2$                                 | 38.73                                         | 38.50                                  | 39.81                                          | 39.27                                  |                                               |                                               |                                      |
|       | TiO$_2$                                 | 5.18                                          | 5.45                                   | 5.33                                           | 5.54                                   |                                               |                                               |                                      |
|       | Al$_2$O$_3$                             | 9.73                                          | 10.34                                  | 12.28                                          | 11.01                                  |                                               |                                               |                                      |
|       | Fe$_2$O$_3$                             | 6.46                                          | 6.83                                   | 6.72                                           | 5.66                                   |                                               |                                               |                                      |
|       | FeO                                     | 12.45                                         | 12.51                                  | 11.13                                          | 10.87                                  |                                               |                                               |                                      |
|       | MnO                                     | 0.24                                          | 0.25                                   | 0.23                                           | 0.26                                   |                                               |                                               |                                      |
|       | MgO                                     | 12.82                                         | 11.54                                  | 8.68                                           | 8.36                                   |                                               |                                               |                                      |
|       | CaO                                     | 12.87                                         | 12.98                                  | 13.80                                          | 14.61                                  |                                               |                                               |                                      |
|       | Na$_2$O                                 | 1.23                                          | 1.32                                   | 1.66                                           | 2.01                                   |                                               |                                               |                                      |
|       | K$_2$O                                  | 0.24                                          | 0.27                                   | 0.35                                           | 0.45                                   |                                               |                                               |                                      |
|       | P$_2$O$_5$                               | 0.04                                          | 0.01                                   | 0.00                                           | 1.96                                   |                                               |                                               |                                      |
|       | **ppm**                                 |                                               |                                        |                                               |                                      |                                              |                                               |                                      |
|       | Sr                                      | 484.16                                        | 520.32                                 | 655.60                                          | 705.24                                  |                                               |                                               |                                      |
|       | Zr                                      | 78.99                                         | 78.72                                  | 79.84                                          | 152.56                                  |                                               |                                               |                                      |
|       | Nd                                      | 25.66                                         | 24.37                                  | 24.31                                          | 96.81                                   |                                               |                                               |                                      |
|       | Ni                                      | 700.99                                        | 653.35                                 | 476.63                                          | 456.86                                  |                                               |                                               |                                      |
|       | Bulk $D_{Sr}$                           | 0.56                                          | 0.59                                   | 0.83                                           | 0.63                                   |                                               |                                               |                                      |
|       | Bulk $D_{Zr}$                           | 0.33                                          | 0.33                                   | 0.37                                           | 0.44                                   |                                               |                                               |                                      |
|       | Bulk $D_{Nd}$                           | 0.53                                          | 0.50                                   | 0.58                                           | 1.41                                   |                                               |                                               |                                      |
|       | Bulk $D_{Ni}$                           | 6.33                                          | 7.62                                   | 6.57                                           | 103.36                                  |                                               |                                               |                                      |

Scenario 1 is for a feldspar-bearing parent and a feldspar-bearing daughter composition. Models A, B and C are for step 1 (i.e. a low Sr–Zr parent and a high Sr–Zr daughter).

Scenario 1 is for a feldspar-bearing parent and a feldspar-bearing daughter composition. Models A, B and C are for step 1 (i.e. a low Sr–Zr parent and a high Sr–Zr daughter). Model D is for step 2, differentiation within the high Sr–Zr group.

−1 to −22% and Zr by −21 to −27%, so that a suitable combination of solutions for both elements was never achieved.

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The modelling of melt compositions yielded useful information for the subsequently calculated EC-RAFC model. Using the equations from Bédard & Wood (1991) and Bédard (2006), a temperature interval of 645°C (−45, +50) to 1257°C (−170, +255) for the Teide–Pico Viejo suite was computed. For the calculation of melt MgO, the equations for both wet and dry melts of Bédard (2006) were tested. The results for dry melt MgO are inconsistent with natural Teide–Pico Viejo data (Bédard’s equation (3b); Table 2), but the equation for wet melts reproduces the natural MgO data very well, particularly between 1 and 6 wt% MgO (Fig. 4). Below 1 wt% MgO, the calculation slightly underestimates the MgO concentration of the most evolved lavas; this is probably an artefact as these values are computed using the anorthite content of anorthoclase crystals.

**Calculation of crystallization temperature and melt Sr concentration**

The modelling of melt compositions yielded useful information for the subsequently calculated EC-RAFC model. Using the equations from Bédard & Wood (1991) and Bédard (2006), a temperature interval of 645°C (−45, +50) to 1257°C (−170, +255) for the Teide–Pico Viejo suite was computed. For the calculation of melt MgO, the equations for both wet and dry melts of Bédard (2006) were tested. The results for dry melt MgO are inconsistent with natural Teide–Pico Viejo data (Bédard’s equation (3b); Table 2), but the equation for wet melts reproduces the natural MgO data very well, particularly between 1 and 6 wt% MgO (Fig. 4). Below 1 wt% MgO, the calculation slightly underestimates the MgO concentration of the most evolved lavas; this is probably an artefact as these values are computed using the anorthite content of anorthoclase crystals.

**EC-RAFC model**

Using the parameters summarized in Table 3, the following results were derived. The mass fraction of anatexic melt $M_\text{an}$ generated from the contaminant is 0.39, whereas the mass fraction of produced cumulate $M_\text{c}$ is 0.338. The mass fraction of solidified recharge magma $M_\text{r}$ amounted to 0.127. This equals a total mass fraction of produced solids of 0.465 versus 0.39 for anatectic melt. The amounts of cumulate and anatectic melt formed in one model step are a result of the elevated solidus temperature, where relatively small changes in temperature (c. 10°C) trigger significant amounts of crystallization.

Modelled trace element concentrations reproduced the concentrations of high Sr-Zr lavas, with Sr increasing to 1132 ppm, Zr to 326 ppm, Nd to 68 ppm and Ni decreasing to 7 ppm. Graphs for $T_{\text{magma}}$, $M_\text{an}$, $M_\text{an}/M_\text{c}$, Zr and Sr, respectively, are shown in Figure 5. Uncertainties in trace element calculations were calculated in the code and did not exceed 4%, except Ni, which below a concentration of 37 ppm showed progressively larger errors of up to 12%.

**Discussion**

**New closed-system models**

The closed-system model fits best when combining a plagioclase-bearing parent with a plagioclase-bearing daughter. This scenario is shown in Fig. 6. Both Sr and Zr concentrations are slightly underestimated by this model compared with the natural daughter composition, but are reasonably close fits to the high Sr-Zr lava data. In detail, however, TiO$_2$ is systematically underestimated in all models of the (parent + plagioclase)/(daughter + plagioclase) combination. Furthermore, this particular model accounts for only a scenario in which plagioclase is present in the parent as well as in the daughter phase assemblages. All other permutations of the system (parent ± plagioclase)/(daughter ± plagioclase) show trace element concentrations that systematically underestimate either Sr or Zr concentrations, or both, or fail to reproduce several oxides. The closed-system models thus appear to require the presence of plagioclase in both parent and daughter, a condition only rarely fulfilled in the Teide–Pico Viejo succession, as only few of the mafic lavas have plagioclase.

Together with the older model of Ablay et al. (1998), which showed considerable inconsistencies in the reproduction of trace element concentrations because of lack of mineral trace element data, the updated closed-system model shows that the closed-system approach may be too simplified to reproduce the complex mechanism of magmatic differentiation. Although the closed-system models for mafic Teide lavas appear to provide a reasonable approximation for their major element variations, we note that calculating a good fit for least-squares regression models usually presents no difficulty. This is especially true when the major element concentrations of the phase assemblage in the samples have been measured. Experience shows that good fits are achieved even when ‘foreign’ mineral data from other settings of comparable tectonic origin are used, probably as a result of the stoichiometric nature of mineral major element data. Mass-balance models based purely on major elements do not provide good constraints on details of differentiation processes. Likewise the incorporation of high-precision plagioclase trace element data into the model of Teide mafic lavas fails to provide 100% accurate fits. A common argument advanced to explain these inaccuracies is variation in the compositions of the fractionated mineral solid solutions. However, given the narrow compositional window that the model covers, it appears unlikely that mineral variations alone can be held responsible for model inaccuracies, as the average mineral compositions extracted from the parent composition were chosen to reflect the data from the natural samples. Considering the plethora of least-squares regression models attempted here, it is concluded that major and trace element closed-system fractionation models are insufficient to explain all major and trace element variations found in mafic Teide lavas (SiO$_2$ <53 wt%).

**Reverse modelling of plagioclase crystallization temperature**

The empirical models of Bédard, Blundy and Bindeman described above permit the calculation of temperature and melt Sr concentrations at the time of plagioclase crystallization. Bindeman et al. (1998) constrained their set of equations to an anorthite content between 40 and 80 mol%, because in this range most natural data show a linear relationship between An content, crystallization temperature and
melt Sr concentrations. Modelled crystallization temperatures yield <1257°C (−170, +255) for low Sr–Zr lavas, whereas high Sr–Zr lavas appear to have crystallized their feldspars below 1009°C (−109, +146) (Fig. 7). Ablay et al. (1998) conducted olivine thermostory, which yielded 1230°C and 1210°C for two alkali basalts (±40°C; equivalent to the low Sr–Zr group), and 1180°C for an evolved basanite (±40°C; equivalent to the high Sr–Zr group). Their clinopyroxene–liquid estimates on the same samples yielded 1224°C, 1211°C and 1197°C, respectively (all ±27°C).

The high-T lavas contain only few and small plagioclases (Montaña Cascajo CA3 and CA1, Montañas Negras NEG) and most probably record the onset of plagioclase crystallization in the Teide–Pico Viejo system. The temperatures modelled by correlation with An content in plagioclase are thus consistent with independent measurements from the same eruptive sequence, albeit at the penalty of much larger errors. Furthermore, the agreement of the empirical feldspar models with the thermometric estimates of Ablay et al. (1998) is better at more calcic feldspar compositions, whereas the crystallization temperatures calculated for plagioclase from high Sr–Zr lavas (An<60) overlap in error by only a small margin. Notably, the heat loss during evolution from low to high Sr–Zr groups recorded by olivine thermometry and cpx–liquid estimates appears comparatively small.

**EC-RAFC model**

The EC-RAFC code was able to reproduce the enrichment of Sr and Zr by crystallization of low Sr–Zr magma and simultaneous assimilation of low-volume anatectic melts from cumulate rocks. The resulting melt possessed trace element compositions characteristic of the high Sr–Zr mafic lavas from the Teide–Pico Viejo succession. The equivalent of the closed-system scenario 1, model A (feldspar-bearing sample CA1 to feldspar-bearing sample REV_bas) is shown in Figure 8. Zirconium is underestimated by 6% for the daughter composition, but is consistent with the range of concentrations found at the mafic end of the high Sr–Zr group. The elements Sr, Nd and Ni are found to consistently reproduce the natural daughter composition, with the enrichment of Sr exceeding the daughter composition by 2%. It thus appears more likely that the combined mechanisms of assimilation and fractional crystallization are responsible for the enrichment of incompatible trace elements among the two observed groups of mafic lavas. This evolutionary link is not reproduced by closed-system fractionation models.

The Teide–Pico Viejo EC-RAFC model requires a mass fraction ratio of crystallized solids and anatectic melt close to unity. Only this approach achieved a modelled melt composition that replicated the natural high Sr–Zr lavas and implies that the magma chamber system must keep a balance between input and output. This is significant in terms of the ‘space problem’ discussed by O’Hara (1998): the presence of pre-existing solid material in magma systems experiencing mantle input cannot be ignored. By rigorously applying thermodynamic and chemical constraints, this study therefore provides a natural example of an ocean island plumbing system that recycles its own products in even the most mafic members of a differentiation series.

The two groups of lavas, low Sr–Zr and high Sr–Zr, are thus related by open-system processes. This implies that both groups of lavas represent different evolutionary stages of the same plumbing system. The high Sr–Zr lavas appear to have experienced extended AFC processes (i.e. thermal equilibration with authigenic cumulate

**Fig. 5.** The evolution of melt compositions from EC-RAFC modelling. $M_a^*$ (mass of anatectic melt generated) and $M_c$ (mass of cumulate formed) are dimensionless. The x-axis is magma temperature; the system thermally equilibrates itself from higher to lower temperatures (left to right). All parameters comply with the natural compositions of the high Sr–Zr lavas.
Fig. 6. Major and trace element variation plots of the Teide fractionation model presented here. Only scenario 1 is shown; that is, when both parent and daughter compositions are feldspar-bearing. Of all scenarios, scenario 1 shows the best fits to natural daughter compositions. Discrepancies between model results and natural samples are indicated by tielines. The two modelling steps (low Sr–Zr to high Sr–Zr and then differentiation within the high Sr–Zr group) are indicated in the graphs. Models A–C belong to the first step and model D to the second step.
rock) and thus achieved a more evolved compositional signature, including trace element concentrations that exceed the possibilities produced by closed-system fractionation. The more primitive low Sr–Zr lavas, in turn, were less affected by AFC processes, perhaps owing to shorter residence times in lower crustal magma chambers. However, olivine from these lavas is in disequilibrium with the mantle (Ablay et al. 1998). Although the low Sr–Zr group seem to have experienced comparatively little modification within magma chambers, the lack of knowledge on the composition of primitive mantle melts prevents an estimation of the full degree of differentiation in these lavas. It is thus possible that the most primitive lavas of the Teide–Pico Viejo system may also have been subject to open-system equilibration with solid material.

The effect of assimilation may be enhanced by the presence of amphibole, as this phase is present in some of the cumulates (Neumann et al. 1999). The solidus depression expected by the release of volatiles from kaersutite breakdown potentially intensifies the anatexis of cumulate rock. Because volatile release from kaersutite is not accounted for in the model, the EC-RAFC modelling represents a minimum estimate of the mass of recycled cumulate or, alternatively, a maximum estimate of the heat exchange required to produce a certain amount of $M_a$. The release of partial melts from the cumulate may thus be stronger than what the model yields or, in nature, less $\Delta T$ may be required to produce a similar amount of anatectic melt. The presence of kaersutite in the cumulate rock thus supports a scenario that is prone to cannibalization of previously formed cumulate rock.

Overall, the results highlight the importance of auto-recycling at depth in ocean islands (see Harris et al. 2000). Notably, a similar mechanism has been suggested for basalts emitted from Piton de la Fournaise, Réunion (Salatín et al. 2010), as well as for other islands of the Canaries (e.g. Gurenko et al. 2010). Several basalt members from the Réunion eruptive phase of 1998 show enrichment of both compatible and incompatible trace elements, which has been interpreted as cannibalism of previously emplaced intrusive rock bodies (i.e. magma–wallrock interaction). O’Hara (1998) iteratively modelled an ocean island plumbing system from its ‘birth’ to eventual subaerial emplacement of lavas and found that the consumption of wall-rock or formerly produced cumulate is an essential factor in the evolution of a plumbing system. Auto-assimilation of previously fractionated mineral phases will strongly increase concentrations of incompatible trace elements in primitive lavas, which can be confirmed on the basis of the models calculated in this study. The EC-RAFC

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**Fig. 7.** Whole-rock Sr data v. modelled crystallization temperature of feldspars in the Tenerife post-collapse lavas. Mafic lavas show a pronounced high at the lower end of the Sr concentration range.

**Fig. 8.** Natural data of mafic Teide lavas compared with Zr, Sr, Nd and Ni concentrations modelled with the EC-RAFC code. Squares are natural data and lines are model results. For each iteration of the EC-RAFC code, error bars are given.
model presented demonstrates the potential of auto-assimilation of previously generated cumulate to enrich Sr and Zr simultaneously, while being consistent with naturally observed concentrations of REE and compatible elements. This result testifies to the difficulty of interpreting mafic ocean island rocks as representative of primitive compositions directly derived from the mantle.

Conclusions

We employed newly available microanalytical data and pre-eruptive melt compositions that were modelled using the empirical equations of Blundy & Wood (1991), Bindeman et al. (1998) and Bédard (2006) to test the closed-system model for Teide–Pico Viejo. The results narrow down the thermal history of Teide mafic magmas and determine that the two broad groups of compositionally diverse mafic magmas are probably not related by closed-system crystal fractionation. Using the given constraints in an EC-RAFC model (Spera & Bohrson 2004, and references therein), which places the geochemical and model data into a thermodynamically constrained framework, the two types of mafic magma are better modelled by open-system processes. The two groups of magma probably reflect different stages of evolution and are thus snapshots of distinct stages of progressive assimilation and fractional crystallization. The high Sr-Zr group experienced AFC-style cumulate recycling within one or multiple magma chambers during extended periods of residence, whereas the low Sr-Zr group is less evolved and is probably the main replenishing magma at depth as it escaped voluminous cumulate recycling and thus resided for short periods in deep magma chambers.

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