10 Magmatic Differentiation in the Teide–Pico Viejo Succession: Isotope Analysis as a Key to Deciphering the Origin of Phonolite Magma

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Abstract

In Tenerife, lavas of the recent Teide–Pico Viejo central complex show a marked bimodality in composition from initially mafic lava (200–30 ka) to highly differentiated phonolite (30–0 ka). Groundmass Sr–Nd–Pb–O and feldspar ^{18}O data demonstrate open system behaviour for the petrogenesis of Teide–Pico Viejo felsic lavas, but contamination by ocean sediment can be excluded due to the low $^{206}Pb/^{204}Pb$ ratios of North Atlantic sediment. Isotope mixing hyperbolae require an assimilant of predominantly felsic composition for the Teide–Pico Viejo succession. Unsystematic and heterogeneous variation of ^{18}O in fresh and unaltered feldspars across the Teide–Pico Viejo succession indicates magmatic

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addition of diverse ^{18}O assimilants, best matched by nepheline syenites that occur as fresh and altered lithic blocks in voluminous pre-Teide ignimbrite deposits. Rare earth element modelling indicates that nepheline syenite needs to be melted in bulk to form a suitable end-member composition. Energy-Constrained Assimilation Fractional Crystallisation (EC-AFC) modelling reproduces the bulk of the succession, which implies that the petrogenesis of Teide–Pico Viejo lavas is governed by the coupled assimilation of nepheline syenite during fractional crystallisation. The most differentiated (and most radiogenic) lava computes to >97.8 % assimilant, likely represented by a nepheline syenite bulk melt that formed by underplating with juvenile mafic material. These recent research developments therefore recognise a wider variability of magmatic differentiation processes at Teide–Pico Viejo than previously considered.

10.1 Introduction

In oceanic islands, the origin of large volumes of felsic volcanic rock has long been a matter of debate (Chap. 9). Due to the absence of large regional tectonic influences and, for most ocean islands, large sedimentary sequences, it had been proposed that crystal fractionation must be the dominant mechanism of differentiation (e.g., Cann 1968; Clague 1978; Garcia et al. 1986; Thompson et al. 2001). At Teide–Pico Viejo, too, the accepted model for magmatic differentiation was for a long time one of pure fractional crystallisation, essentially because detection of assimilation was not possible by traditional petrological means (e.g., Ablay et al. 1998). Major and trace element variations of the Teide–Pico Viejo complex combined with geothermobarometry and estimates of pre-eruptive volatile contents have allowed the establishment of a fractionation sequence that invoked 88 % removal of crystals for the generation of phonolite. Moreover, the presence of amphibole in some Pico Viejo lavas indicated the presence of two distinct petrological lineages for Pico Viejo and Pico Teide and, hence, two plumbing systems were postulated to exist with different depths for their main magma chambers. This interpretation of Teide–Pico Viejo magmatic differentiation processes involved fractional crystallisation exclusively, and hence the model described Teide as a closed system, i.e., a system in which no external material enters the magma and only energy is exchanged with the surrounding wall rock (e.g., cooling). Ablay et al. (1998), however, noted that certain trace element variations were not explained by the pure crystal fractionation model. The authors invoked small additions of zeolite and hydrothermally altered material to explain these variations, but until recently no in-depth petrogenetic investigation using isotopic methods was available to test this model. The focus of this chapter is the quantification of crustal influences using Sr, Nd, Pb and O isotope geochemistry.

10.2 The Application of Radiogenic Isotopes in Igneous Petrology

A reliable way to resolve whether a magmatic system is open or closed to the influx of foreign material is the study of radiogenic isotopes ratios in minerals and rocks. If the mantle-derived magmatic source is assumed to have a relatively constant isotope composition at a certain point in time, as is the case in Tenerife (Simonsen et al. 2000), isotope ratios in magma may change only by two principal means, radioactive decay and/or mixing with material of differing isotopic composition.

Radioactive decay requires millions of years to change the isotope ratios of Sr, Nd and Pb at a detectable level. For example, the half-life of

^{87}Rb, which decays to ^{87}Sr and thus slowly increases the ratio of $^{87}Sr/^{86}Sr$, is thought to be 48.8 Ga (e.g., Dickin 2005). However, over the geologically brief episode in which the Teide–Pico Viejo edifice has been constructed (<200 ka), radioactive decay is too minute to significantly affect the $^{87}Sr/^{86}Sr$ ratios of the Teide–Pico Viejo rocks and, thus, the ratios would effectively remain constant in a closed system situation.

In turn, if the magmatic system is open, assimilation of external material may change the isotopic composition of magma when material of a distinct isotopic composition is admixed. Consider a magma with an Sr isotope ratio of 0.703 that assimilates material, e.g., country rock with an Sr isotope ratio of 0.705, in this case more ^{87}Sr than ^{86}Sr is fluxed into the magma, consequently raising the ratio of $^{87}Sr/^{86}Sr$ in the now contaminated magma mixture (e.g., Duffield and Ruiz 1998). The final Sr isotope ratio of this mixture will fall somewhere between 0.703 and 0.705, depending on the respective Sr concentrations in magma and country rock and the relative volumes of magma and country rock involved.

As isotope ratios are virtually unaffected by radiogenic decay in a young system such as Teide-Pico Viejo, they become an extremely powerful tool for the detection of assimilation. Measured isotope ratios that are different from the mantle source must have formed by modification of the magma by the addition of external material with a different isotopic composition. Isotope ratios can thus be used as fingerprints to identify rock types that may have been assimilated during magma evolution and furthermore allow calculation of the amount of material that must have been assimilated (e.g., Troll et al. 2005; Meade et al. 2009). Assimilation can strongly alter and accelerate magmatic differentiation and promotes felsic magma production, making this an important aspect of magma development to understand.

As the Teide–Pico Viejo system is geologically speaking very young (<200 ka), it provides an ideal testing ground for the application of radiogenic isotopes in constraining magma chamber processes and potential crustal influences on ocean island magmatic suites. Here, a thorough update of the magmatic differentiation processes that are recognised at Teide–Pico Viejo using Sr–Nd–Pb and O isotopes is summarised from the work of Wiesmaier (2010) and Wiesmaier et al. (2012).

10.3 Previous Work and Research Techniques

In a recent study, the radiogenic isotope composition of 58 of the 64 known eruptions of the Teide–Pico Viejo succession have been analysed (Wiesmaier et al. 2012). Some of these eruptions comprise multiple phases (Carracedo et al. 2007). A total of 61 groundmass samples were analysed from the three groups of Teide–Pico Viejo lavas (mafic, transitional and felsic), for their Pb, Sr and Nd isotopic composition. Fresh groundmass represents the very last melt composition before complete solidification and is, when properly separated, completely unaffected by any masking effects from the accumulation of pheno-/xenocrysts and thus allows melt processes to be constrained reliably (e.g., Marsh 2004; Kinman et al. 2009). Moreover, five sedimentary rocks of exhumed pre-island seafloor from Fuerteventura were analysed to serve as potential end-members for the isotopic composition of non-magmatic rocks that may lie underneath or within the islands (e.g., Stillman et al. 1975; Hobson et al. 1998; Hansteen and Troll 2003).

Feldspar separates from 15 lava flows were also analysed for their $\delta^{18}O$ composition at the University of Oregon, USA. Plagioclase phenocrysts were analysed by laser fluorination to determine $\delta^{18}O$ values, the maximum analytical uncertainties on $\delta^{18}O$ measurements are estimated at 0.15 ‰. For details of the analytical methods for both radiogenic and stable isotopes the reader is referred to Wiesmaier (2010) and Wiesmaier et al. (2012). A summary of results for all three sets of radiogenic isotope systems and oxygen isotopes are reported in Table 10.1.

Table 10.1 Overview of the isotope composition of Teide–Pico Viejo deposits and Fuerteventura sediments.

Isotope systems	Mafic	Transitional	Felsic	Sediment
$^{87}Sr/^{86}Sr$	0.703040(21)–0.703229(18)	0.703094(20)–0.703332(17) *comparable to mafic*	0.703091(2)–0.704900(16) *higher than mafic/transitional*	0.703473(21)–0.707684(21)
$^{143}Nd/^{144}Nd$	0.512901–0.512991 (± 6–45)	0.512916–0.512956 *narrower range than mafic*	0.512924–0.512950 *yet narrower range*	
$^{206}Pb/^{204}Pb$	19.5050(22)–19.8142(22)	19.7493(26)–19.7743(26) *narrow range compared to mafic*	19.7541(28)–19.7816(24) *narrow range compared to mafic*	18.5307(13)–19.7447(01)
$^{207}Pb/^{204}Pb$	15.5919(22)–15.6456(24)	15.6102(24)–15.6337(28) *narrower range than mafic*	15.5288(22)–15.6174(26) *much lower than mafic/trans.*	15.6263(26)–15.6767(14)
$^{208}Pb/^{204}Pb$	39.4490(68)–39.6371(68)	39.5536(70)–39.6067(80) *narrower range than mafic*	39.5316(72)–39.6001(68) *narrower range than mafic*	38.2678(70)–39.6810(42)
$\delta^{18}O$ [‰]	5.43–5.84	5.46–5.88 *comparable to mafic*	5.88–5.99 *higher values*	

Results from groundmass isotope analyses. Errors for Sr, Nd and Pb isotope ratios are 2 × Standard Deviation. Felsic lavas show an elevation in Sr isotope ratios compared to the other lavas. Compared to mafic lavas, in turn, transitional and felsic lavas show a strong confinement in $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ ratios. Oxygen isotope values of feldspar phenocrysts show rather heterogeneous values in mafic and transitional lavas, and a small increase in felsic lavas. *Data* Wiesmaier (2010) and Wiesmaier et al. (2012)

10.4 Sr-Nd–Pb–O Systematics at Teide-Pico Viejo

Mafic and transitional lavas overlap considerably in $^{87}Sr/^{86}Sr$ ratios, whereas the felsic lavas yield $^{87}Sr/^{86}Sr$ ratios of 0.703091(2)–0.704900(16), significantly higher than the mafic and the transitional compositions. The sediment samples are higher than both mafic and transitional samples, but partly overlap with the felsic lavas.

Mafic lavas yield variable $^{143}Nd/^{144}Nd$ ratios of 0.512901–0.512991. Transitional samples also show some variation, but are confined to a smaller interval of $^{143}Nd/^{144}Nd$. Felsic samples plot in an even tighter $^{143}Nd/^{144}Nd$ range from 0.512924 to 0.512950.

The $^{206}Pb/^{204}Pb$ ratios of transitional and felsic lavas show a peculiar behaviour compared to the mafic lavas. Mafic lavas show a spread in values that is consistent with previously published data from other mafic deposits in Tenerife. The transitional and felsic lavas, in turn, are confined to a very narrow interval of $^{206}Pb/^{204}Pb$ values, with felsic lavas yielding much lower values for $^{207}Pb/^{204}Pb$ than what is found in the mafic lavas. In $^{208}Pb/^{204}Pb$, mafic lavas completely encompass the felsic and transitional lava data range in their variability.

Oxygen isotope ratios in feldspars from mafic lavas (presented relative to the international standard SMOW) range from +5.43 ± 0.11 ‰ to +5.84 ± 0.02 ‰. Feldspars from transitional lavas display values from +5.82 ± 0.29 ‰ to +5.88 ± 0.11 ‰, with the exception of one outlier at +5.46 ± 0.11 ‰. The felsic lavas give feldspar oxygen isotope values that range from +5.88 ± 0.11 ‰ to +5.99 ± 0.11 ‰, i.e., only marginally higher than those from mafic samples.

Fig. 10.1 The twin Pico Viejo and Teide volcanoes are a spectacular example of felsic strato-cones in oceanic islands (www.fotosaereasdecanarias.com)

10.5 Discussion

The data permit several simple qualitative deductions that will set the scene for a more in-depth interpretation. Most importantly, the Sr, Nd, Pb and O isotope data of Teide–Pico Viejo lavas show a strong variability in isotope ratios, which exceeds the variability of the uncontaminated mantle signal in Tenerife. For example, the $^{87}Sr/^{86}Sr$ ratio of the mantle signal is thought to range between 0.7031 and 0.7033 (Simonsen et al. 2000). Although this is consistent with the bulk of Teide lavas that show a common $^{87}Sr/^{86}Sr$ range of 0.7031–0.7033, two felsic lavas (phonolites) exceed this Sr isotope baseline considerably and reach up to 0.7049 (Table 10.1). This implies that at some stage during the evolution of Teide magma, material of a different isotopic composition was introduced. The magmatic plumbing system beneath Teide–Pico Viejo must therefore be open in order to undergo chemical exchange with fluids and/or surrounding wall rock (Fig. 10.1).

The Pb isotope data of felsic Teide–Pico Viejo lavas have a very uniform $^{206}Pb/^{204}Pb$ ratio. This is, once more, distinct from the mafic lavas, which are variable in $^{206}Pb/^{204}Pb$ and so delineate a field of 'baseline' Pb isotope ratios comparable with other ocean islands (Fig. 10.2). This alone would not be unusual, but in addition, the felsic lavas possess much more variable $^{207}Pb/^{204}Pb$ ratios than the mafic lavas. Although the $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios in felsic lavas are consistent with the range of Pb isotope data so far found in Tenerife rocks, the combination of uniform $^{206}Pb/^{204}Pb$ and very low $^{207}Pb/^{204}Pb$ composition in the Teide felsic lavas is uncommon. The Sr and Pb isotope ratios therefore indicate that the Teide–Pico Viejo succession has formed by open-system processes, assimilating a component of distinct isotope composition during the differentiation of the most evolved (i.e., most felsic) magmas at the Teide–Pico Viejo central complex.

10.5.1 Sediment Contamination?

Judging from the Sr isotope data alone, it appears possible that sediment may have been taken up by magma consequently altering its $^{87}Sr/^{86}Sr$ composition. The Jurassic oceanic crust below Tenerife is overlain by thick sedimentary sequences with elevated $^{87}Sr/^{86}Sr$ that magma has to traverse before reaching the surface (Sun 1980; Hoernle et al. 1991; Hoernle 1998; Hansteen and Troll 2003; Aparicio et al. 2010; Troll et al. 2012). Atlantic sediment may also be uplifted into the island's core and is thus potentially present during magmatic ascent in the Canaries (Stillman et al. 1975; Robertson and Stillman 1979; Hansteen and Troll 2003).

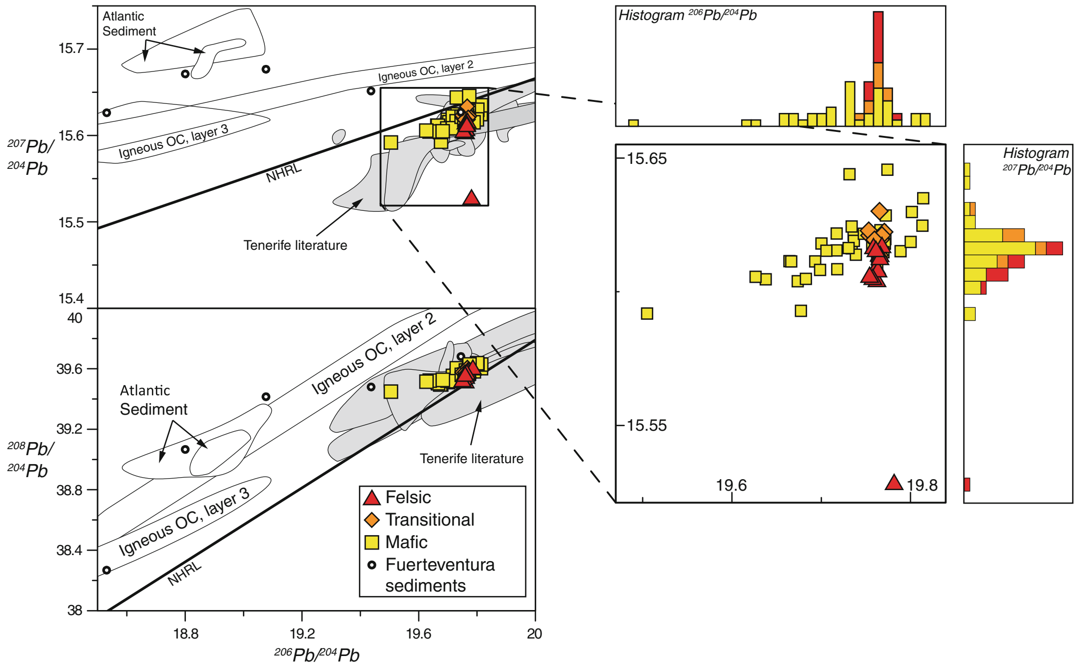


Fig. 10.2 Results from Pb isotope analyses combined with histograms of $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ ratios of the Teide–Pico Viejo succession. All errors are 2SD and are included in the symbols. Note the lack of a trend in the Teide–Pico Viejo succession towards Atlantic sediment compositions. Transitional and felsic lavas show a peak in $^{206}Pb/^{204}Pb$ ratio distribution at around 19.76, similar to mafic lavas. In contrast, felsic lavas are off this mafic peak in $^{207}Pb/^{204}Pb$ ratio, indicating an open system. Note the confinement of transitional and felsic lavas to a narrow range of $^{206}Pb/^{204}Pb$ ratios. Data for Tenerife are from Sun (1980), Simonsen et al. (2000), Abratis et al. (2002), Gurenko et al. (2006), and Wolff et al. (2000); data for oceanic crust and Atlantic sediment were taken from Sun (1980), Hoernle et al. (1991) and Hoernle (1998)

However, since sediment also contains significant amounts of Pb, sediment contamination would have to be detected in both the Sr and the Pb isotope systems, but this is not the case. Atlantic sediments always have lower $^{206}Pb/^{204}Pb$ and much higher $^{207}Pb/^{204}Pb$ compositions (Fig. 10.2). In the Teide–Pico Viejo succession, a Pb isotopic trend toward sediment composition is not discernible. Despite the comparable $^{87}Sr/^{86}Sr$ ratios in sediment and phonolite, Atlantic sediments are therefore unlikely to have entered the magmatic plumbing system of Teide–Pico Viejo in appreciable quantities. This implies, in turn, that the high Sr isotope ratios found in some of Teide's most evolved phonolites must stem from material other than sediment.

10.5.2 Constraints on the Assimilant

So far we have established that the open system of Teide–Pico Viejo volcano assimilated a non-sedimentary component. This yet to be defined assimilated material (or *assimilant*), can be further constrained by Sr–Nd isotope modelling. Isotope modelling allows us to calculate the isotopic composition of a mixture of two different end-members. The resulting mixing curves, or mixing hyperbolae, trace the possible mixtures of the two end-members, from 100:0 to 0:100 (end-member A:B). Of course, magmatic processes are not bound to simple mixing, but this type of model helps to detect first order genetic relationships in a sequence of rock samples and helps to further constrain the composition of the assimilant.

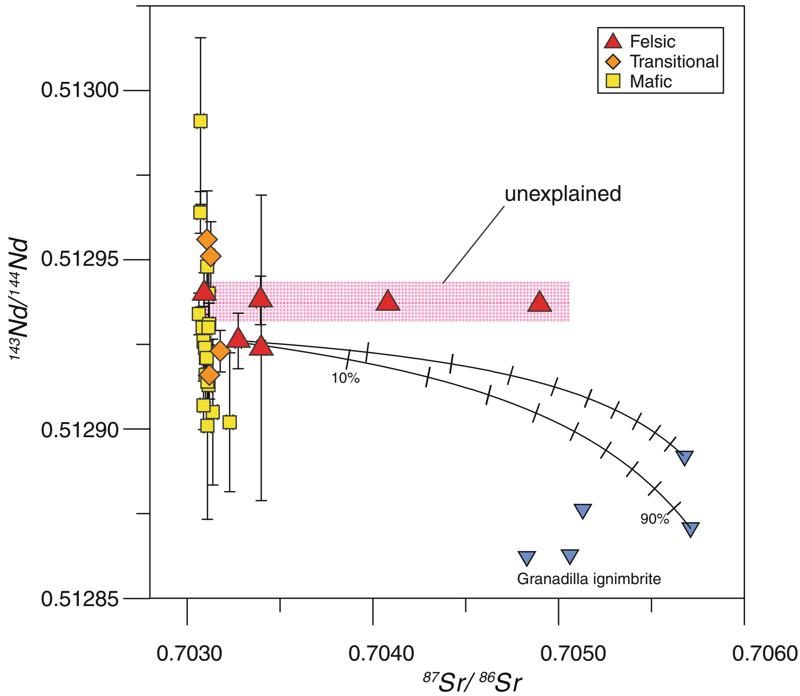


Fig. 10.3 $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ of Teide–Pico Viejo lavas compared to data from the Granadilla ignimbrite (Palacz and Wolff 1989). Granadilla ignimbrite data are the only available high $^{87}Sr/^{86}Sr$ data from Tenerife, but are insufficient to explain the Teide–Pico Viejo isotopic variations in full

In the case of Teide–Pico Viejo, a high $^{87}Sr/^{86}Sr$ assimilant is required. As sediment has been ruled out, we need to look for an end-member that may be part of the island itself. The ~570 ka Granadilla ignimbrite is the only known deposit in Tenerife with $^{87}Sr/^{86}Sr$ ratios sufficiently high to serve as a potential assimilant (Palacz and Wolff 1989). The Granadilla ignimbrite is the product of a caldera-forming eruption within the Upper Group of the Las Cañadas Volcano deposits (Wolff and Palacz 1989; Martí et al. 1994, 1997; Bryan et al. 2002) and bears abundant nepheline syenite blocks of co-genetic composition. This material very likely abounds at depth below Teide volcano, and is thus theoretically available as an assimilant.

However, the Granadilla ignimbrite data also fail to reproduce the full pattern defined by the Teide–Pico Viejo lavas. The two Granadilla–Teide mixing curves in Fig. 10.3 demonstrate this. Furthermore, Granadilla ignimbrite samples also possess lower $^{206}Pb/^{204}Pb$ ratios than the felsic lavas (19.621–19.734 versus 19.754–19.782). Thus, Teide–Pico Viejo differentiated magma has not been strongly affected by material of the Granadilla eruption.

However, this exercise does provide additional information on the assimilant. We know that the assimilant must have had a higher $^{87}Sr/^{86}Sr$ ratio than sample MB7 ($^{87}Sr/^{86}Sr = 0.7049$). From 153 measurements found in the literature and the data presented here, we also know that in Tenerife, high $^{87}Sr/^{86}Sr$ ratios are only found in rocks of low Sr concentration. This implies a highly differentiated rock, comparable to the Granadilla ignimbrite. Moreover, $^{206}Pb/^{204}Pb$ values of the contaminant are required to be similar to the ratios found in felsic lavas but need to be lower in $^{207}Pb/^{204}Pb$. Few rocks have these characteristics, but the Diego Hernández Formation basalts for example, provide suitable Pb isotope ratios. Finally, mafic Las Cañadas rocks possess appropriate $^{143}Nd/^{144}Nd$ values, which are higher than the relatively low Granadilla values (see Simonsen et al. 2000).

Mixing modelling can also be performed with a hypothetical assimilant. The aim is to ascertain what type of assimilant would best reproduce the compositional features of the Teide–Pico Viejo succession. This hypothetical assimilant is based on the Granadilla ignimbrite composition, but

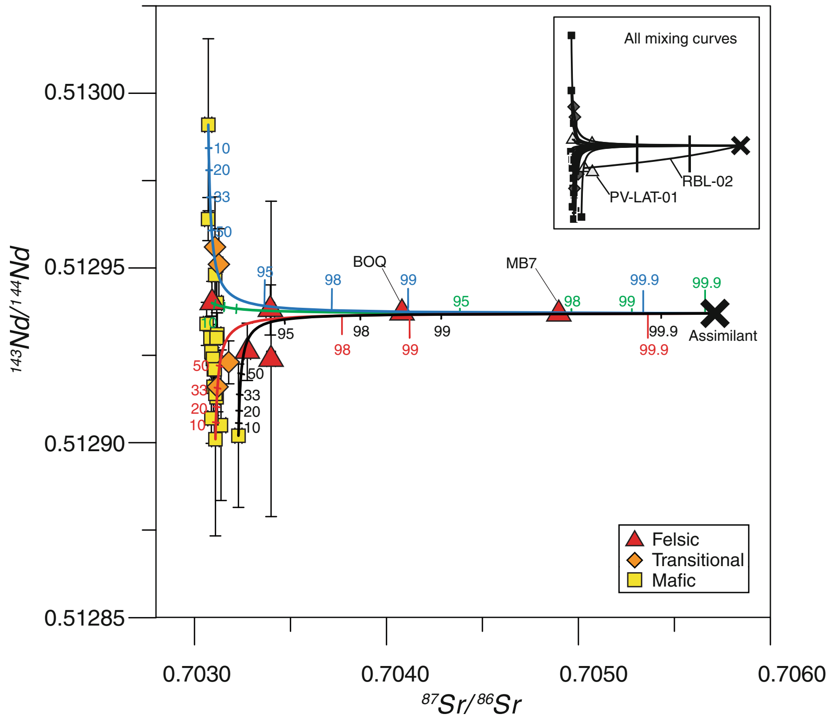


Fig. 10.4 Plot of $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$ of Teide–Pico Viejo lavas, modelled by using a hypothetical assimilant (*black cross*). Four representative mixing hyperbolae are presented between the hypothetical assimilant and three mafic lavas (*curves*: *red*, *black* and *blue*) and one felsic lava (*green curve*). *Numbers* indicate percentage of assimilant involved in the mixture. Hyperbolae of all remaining calculations are shown in the *inset*. The true assimilant likely was of felsic composition as low Sr/Nd ratios are required by the shape of the mixing hyperbolae. Note that to successfully model the sample MB7, between 97.8 and 99.5 % assimilant is required

with higher $^{143}Nd/^{144}Nd$ and suitable $^{206}Pb/^{204}Pb$ values. The mean Nd ratio of the Teide-Pico Viejo felsic lavas was assumed as the $^{143}Nd/^{144}Nd$ value for the assimilant (0.512937, n = 6), and the uniform $^{206}Pb/^{204}Pb$ ratios of the same felsic lavas were used as the Pb isotope ratio of the assimilant. Using comparable Sr and Nd concentrations and, consequently, a low Sr/Nd ratio in the hypothetical assimilant ensures that the assimilant bears the Sr, Nd and Pb signatures of an idealised highly differentiated Tenerife rock.

The resulting mixing hyperbolae not only encompass the felsic lavas within a single mixing relationship, but also include all transitional and mafic lavas, that is, the entire differentiation sequence from mafic to felsic lavas (Fig. 10.4). Being able to model an entire volcanic succession by invoking a single, isotopically feasible, end-member suggests a convincing genetic relationship for the Teide–Pico Viejo lavas and indicates that similar material was assimilated throughout the 200 ka of Teide–Pico Viejo evolution. In addition, the curvatures of the mixing hyperbolae provide strong evidence for the composition of the assimilant. To reproduce the Teide–Pico Viejo data, the mixing hyperbolae require a low Sr/Nd ratio in the assimilant, if this ratio is changed, the curves no longer reproduce the Teide data. A low Sr/Nd most likely represents an assimilant of felsic composition.

Furthermore, mafic lavas seem to include rather little assimilant, but the more felsic the lavas become, the higher the percentage of assimilant they appear to have incorporated. The Sr–Nd fingerprints of felsic lavas contain between 77 and 99.78 % of this hypothetical assimilant, regardless of whether the composition of a mafic, a transitional or a low—$^{87}Sr/^{86}Sr$ felsic lava is used as magmatic end-member. The felsic lava with the highest $^{87}Sr/^{86}Sr$ ratio, sample MB7, requires an end-member percentage of >97.8 % of the hypothetical felsic composition. The isotopic composition of Teide–Pico Viejo felsic lavas therefore displays a strong influence from a highly differentiated assimilant that increases dramatically with degree of differentiation.

These indications for a felsic assimilant during Teide–Pico Viejo magmatic evolution are consistent with phase equilibria considerations, melt inclusion analysis and geothermobarometry experiments, which indicate a shallow depth of origin for felsic magmas in Tenerife (Wellman 1970; Andújar et al. 2008, 2010). From these experiments, it is possible to infer the pressure at which a certain phenocryst or a crystal assemblage may have formed. The experimental results suggest that nepheline syenite (the deep plutonic equivalent of the pre-Teide Las Cañadas ignimbrites) and Teide phonolite both crystallised at 4–6 km depth, i.e., when Teide phonolite magma crystallised inside the volcano it was likely surrounded by these pre-Teide nepheline syenite rocks.

10.5.3 Heterogeneous Oxygen Isotope Composition of the Assimilant

The $\delta^{18}O$ ratios in feldspar crystals and groundmasses are consistent with open system differentiation. Closed-system fractional crystallisation is thought to continually raise $\delta^{18}O$ values at a small, but defined rate with differentiation (grey fields in Fig. 10.5), whereas uptake of non-magmatic material usually generates a deviation from this pattern. At Teide–Pico Viejo both low and high $\delta^{18}O$ components are discernible, albeit only in single eruptions and hence not systematically. Most data points plot within error of the closed system field for the alkali-rich series, with three samples yielding values significantly lower than that (Fig. 10.5). At very high degrees of differentiation, two groundmass samples show

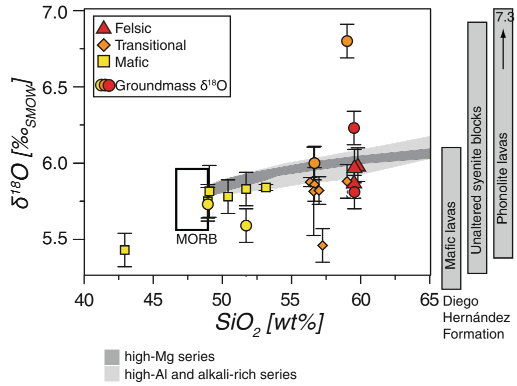


Fig. 10.5 Oxygen isotope ratios of feldspar and groundmass separates versus whole-rock SiO_2. *Triangles*, *squares* and *diamonds* represent feldspars, *circles* are groundmass. *Grey shaded arrays* denote closed-system oxygen isotope fractionation (from Bindeman 2008). Teide–Pico Viejo data deviate from these arrays and thus demonstrate an open system. *To the right*: *grey bars* are data from the Diego Hernández Formation from Wolff et al. (2000). Teide data overlap with the range of values found in Diego Hernández ignimbrites and nepheline syenites, consistent with Diego Hernández-type rocks being a potential assimilant

high $\delta^{18}O$ values, which are not reproduced by the feldspar crystals hosted in these samples, indicative of the late-stage addition of a high-$\delta^{18}O$ component to the melt.

The $\delta^{18}O$ data of the highly differentiated members of the Diego Hernández Formation and the enclosed nepheline syenite blocks (Wolff et al. 2000) show an even larger variability in $\delta^{18}O$, which moreover, overlaps the values found for the Teide–Pico Viejo succession. Such a heterogeneous assimilant is likely to produce variability in $\delta^{18}O$ ratios across a series of eruptions separate in time. The $\delta^{18}O$ signatures found in Teide–Pico Viejo lavas are therefore best explained by the uptake of highly differentiated material of a heterogeneous $\delta^{18}O$ composition.

10.5.4 Bulk Melting of Country Rock

An important question for the assimilation of foreign material into magma is whether entire fragments of country rock (i.e., xenoliths) or a partial melt of this country rock is incorporated. Partial melting describes the selective melting of a protolith, i.e., those phases with a lower melting point melt first (e.g., Duffield and Ruiz 1998). For example, a 50 % partial melt of a rock is not simply cutting the rock in half and melting one of the two halves, but rather selectively melting 50 % of its constituents, particularly those that melt at lower temperatures. As a result of partial melting, the melt produced usually has a dramatically different composition from the original protolith (e.g., Holloway and Bussy 2008). This is best reflected in the trace element concentrations of a partial melt. Incompatible elements are trace elements that do not fit well into crystal lattices of common magmatic crystals because of their large ionic radius. Instead, these elements prefer the liquid phase and will therefore be enriched in the partial melt and depleted in the solid residue. Thus incompatible elements are particularly useful as tracers of partial melting.

Batch partial melting calculations of the Diego Hernández nepheline syenite allow us to estimate both the degree of partial melting and the composition of the partial melt produced. The Rare Earth Elements (REE) are especially well-suited for use in partial melting calculations, because of their systematic variation of ionic radius at a near-constant valent state, the so-called *lanthanide contraction*. This means that the relative behaviour of two neighbouring elements is very predictable, as these cations systematically partition into crystals or melt. In a plot of Gd/Yb versus La/Sm, for example, lower degrees of partial melting cause higher Gd/Yb and La/Sm ratios (and vice versa).

Using partial melts of the Diego Hernández Formation nepheline syenite as an assimilant, the mixing model only reproduces Teide–Pico Viejo phonolites above a melt fraction of ca. F = 0.95. Using bulk melts of nepheline syenite however, (F = 1) reproduces the felsic Teide lavas well. Note that 'altered' nepheline syenite provides the best fit in these calculations, and is thus more likely than assimilating a 'fresh' nepheline syenite (Fig. 10.6).

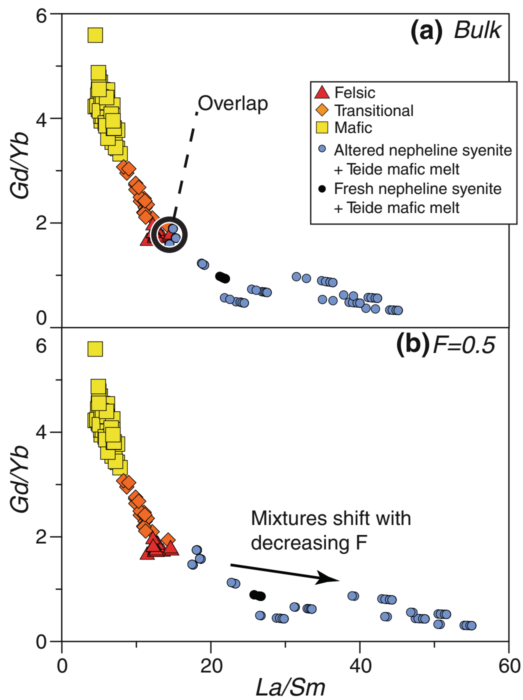


Fig. 10.6 Results of rare earth element modelling, using the mixing percentages derived from isotope modelling. To constrain the degree of partial melting of country rock, Teide–Pico Viejo lavas (*squares*, *diamonds*, *triangles*) are compared with mixtures of Diego Hernández batch melts and Teide–Pico Viejo lavas (*crosses*). The degree of partial melting of Diego Hernández rocks is given in the *upper right-hand corner*. Teide felsic lavas are best reproduced by mixing Teide mafic lava compositions with bulk melts of Diego Hernández samples. Lower degrees of partial melting of Diego Hernández rocks (< 0.95) shifts the resulting mixtures towards higher La/Sm ratios that increasingly differ from the observed Teide lava compositions

10.5.5 Quantification of Differentiation Processes at Teide–Pico Viejo

In the preceding discussion, radiogenic and stable isotope data from Teide–Pico Viejo lavas were shown to demonstrate the influence of a highly differentiated igneous assimilant. Moreover, the underlying calculations support the bulk incorporation of that assimilant. While these mixing calculations are a perfectly valid first order approximation, magmatic differentiation is commonly attributed to assimilation and fractional crystallisation (DePaolo 1981). To quantify the interplay of fractionation and assimilation at Teide–Pico Viejo, the EC-AFC model after Spera and Bohrson (2001) was employed. This complex but user-friendly code embeds assimilation and fractional crystallisation into a geochemical, isotopic and thermodynamic framework and thus permits more realistic assumptions on the intensity and interplay of the various differentiation processes (Spera and Bohrson 2001, 2002, 2004).

Here, an EC-AFC model is shown for one batch of hot, mafic magma that thermally equilibrates with a surrounding, cooler and highly differentiated assimilant of nepheline syenite composition. All information that has been gathered so far is included in this model: isotope and geochemical data on both Teide–Pico Viejo and the hypothetical assimilant, crystallisation depths and a steep geothermal gradient of 100 °C/km, observed at Teide (http://www.petratherm.com.au/_webapp_117699/Canary_Islands). Specific heat capacities and crystallisation/fusion enthalpies were calculated using the average compositions of Tenerife Granadilla ignimbrite.

The felsic assimilant and the chosen thermal parameters reproduce the geochemical and isotopic variations in Teide–Pico Viejo lavas well (Fig. 10.7). The EC-AFC curves match the entire differentiation sequence in Pb, Zr and Hf composition. Sr, Ba and Nd curves reproduce all compositions except for the samples of intermediate concentrations. This, however, is an artefact of the EC-AFC code, because abrupt changes in bulk compatibility of trace elements, a likely phenomenon in nature, are not accounted for.

Isotope ratios are well reproduced, too. As Pb and Nd ratios are very variable in mafic lavas, several mafic end-member compositions were tested (see model curves in Fig. 10.7). All of the mafic end-members trend towards the same felsic end-member isotope composition during thermal equilibration and replicate the naturally occurring pattern of isotope compositions. Equally, the $^{87}Sr/^{86}Sr$ ratios of the Teide succession are well explained by these mixing hyperbolae, except for one outlier. By and large, the EC-AFC model demonstrates that the formation of felsic Teide–Pico Viejo magma is consistent with assimilation of felsic rock with simultaneous crystal fractionation from a mafic parent.

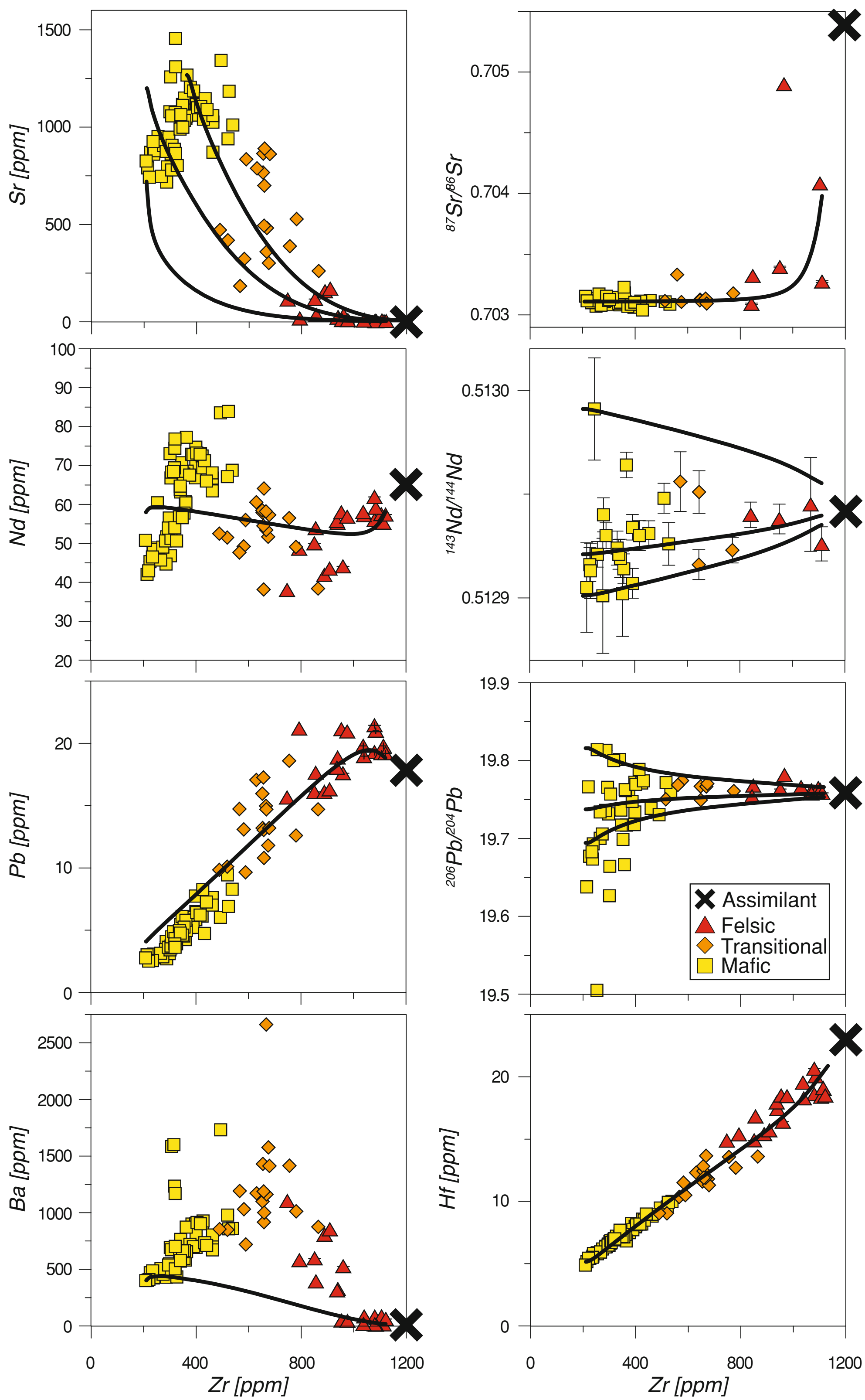
The model also confirms details revealed by the REE batch melting calculations and Sr–Nd isotope modelling results. Firstly, the EC-AFC model requires felsic country rock to be melted wholesale, and secondly, assimilation appears more dominant with higher differentiation of magma.

10.5.6 Mechanisms for Crustal Melting

The only sample composition that is not being replicated by EC-AFC is one sample from Montaña Blanca (MB7). This is the lava with the highest degree of differentiation found in the entire Teide–Pico Viejo suite. Perhaps processes additional to combined assimilation and fractional crystallisation have influenced this particular magma.

In a plot of $^{87}Sr/^{86}Sr$ versus $1/^{86}Sr$, the felsic lavas either show high $^{87}Sr/^{86}Sr$ ratios, low ^{86}Sr concentrations (high $1/^{86}Sr$) or a combination of both. The felsic samples RBL-02 and BOQ plot to the right hand side at high $1/^{86}Sr$ values (Fig. 10.8). Using the felsic assimilant deduced from isotope and trace element constraints, the EC-AFC curves reproduce the samples BOQ and RBL-02, but fall short of explaining the Sr isotope composition of sample MB7. Instead, four of the felsic lavas (including Montaña Blanca) define a linear array, which indicates a mixing relationship with the felsic assimilant. We previously mentioned that fractional crystallisation and assimilation would be the main drivers of magmatic differentiation. For this *individual* lava, however, the isotope data point to more than 98 % of assimilant involved in the formation of sample MB7 (Montaña Blanca). This supports the view that phase 7 of the Montaña Blanca volcano was formed by large scale crustal melting with only minor amounts ($\sim$2 %) juvenile magma. Essentially, such large amounts of assimilant imply that the MB7 magma was a crustal melt and was 'contaminated' to a small percentage by mafic magma.

It is therefore maybe not surprising that the EC-AFC model failed for this sample. The EC-


Sr [ppm]
1500
1000
500
0
87Sr/86Sr
0.705
0.704
0.703
Nd [ppm]
100
90
80
70
60
50
40
30
20
143Nd/144Nd
0.5130
0.5129
Pb [ppm]
20
10
0
206Pb/204Pb
19.9
19.8
19.7
19.6
19.5
Assimilant
Felsic
Transitional
Mafic
Ba [ppm]
2500
2000
1500
1000
500
0
Hf [ppm]
20
10
0
0
400
800
1200
Zr [ppm]

◀ **Fig. 10.7** Results from EC-AFC modelling. Teide–Pico Viejo succession in *yellow-orange-red symbols*, "x" marks the assimilant composition. Zirconium was used as an index of differentiation on the x-axis. Trace elements Sr, Nd, Pb, Zr, Hf and Ba and isotope ratios $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ have been modelled; *black* curves are model results. All trace elements and isotope ratios are well reproduced, indicating a strong agreement between our model and the inferred differentiation processes at work. One exception however, is, when bulk partition coefficients change from incompatible to compatible, at this point intermediate compositions are not well reproduced by the code employed. Note that the sample with the highest $^{87}Sr/^{86}Sr$ ratio (MB7) is also not always reproduced by the model (see text for details)

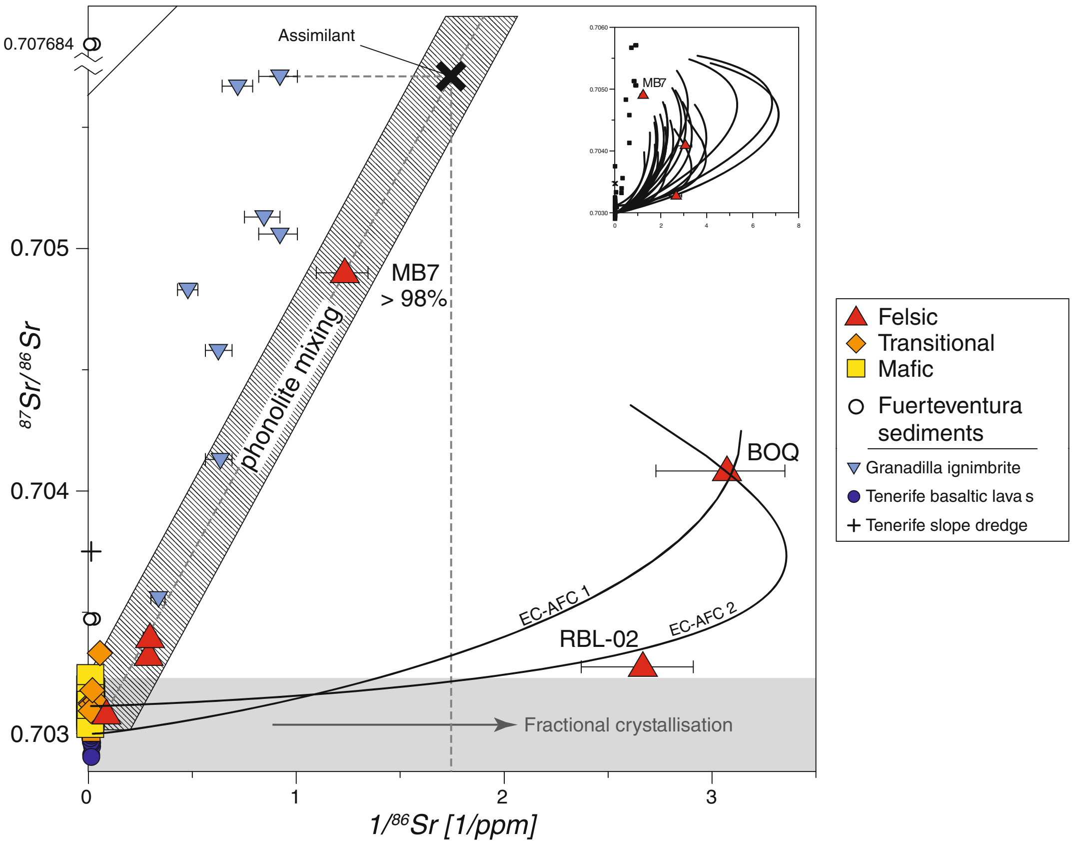


Fig. 10.8 Groundmass $^{87}Sr/^{86}Sr$ versus $1/^{86}Sr$ of Teide–Pico Viejo lavas. The Sr concentration of the hypothetical end-member used for EC-AFC modelling was computed to be 5.89 ppm, using Granadilla ignimbrite Sr isotope ratios. Errors (2SD) are contained within symbols when invisible. Strontium concentrations of Fuerteventura sediments are from Deegan (unpublished data). Samples BOQ and RBL-02 plot at low ^{86}Sr concentrations and are successfully modelled by EC-AFC. Sample MB7 cannot be modelled by EC-AFC using the thermal constraints inherent to the Tenerife setting. Instead, this sample opens a straight mixing array with other felsic lavas and the assimilant, indicating a crustal melt origin. End-member data are from Palacz and Wolff (1989), Simonsen et al. (2000) and Abratis et al. (2002)

AFC model describes the combined effects of wall-rock assimilation and fractional crystallisation within a single magma chamber. However, when pockets of felsic melt (e.g., molten country rock) form around mafic magma chambers without touching them or if they are physically unable to mix (e.g., Marshall and Sparks 1984), it is mainly heat that is transferred from the magma for assimilation and no significant chemical exchange takes place (Petford and Gallagher 2001; Holloway et al. 2008). In this case, AFC models are not

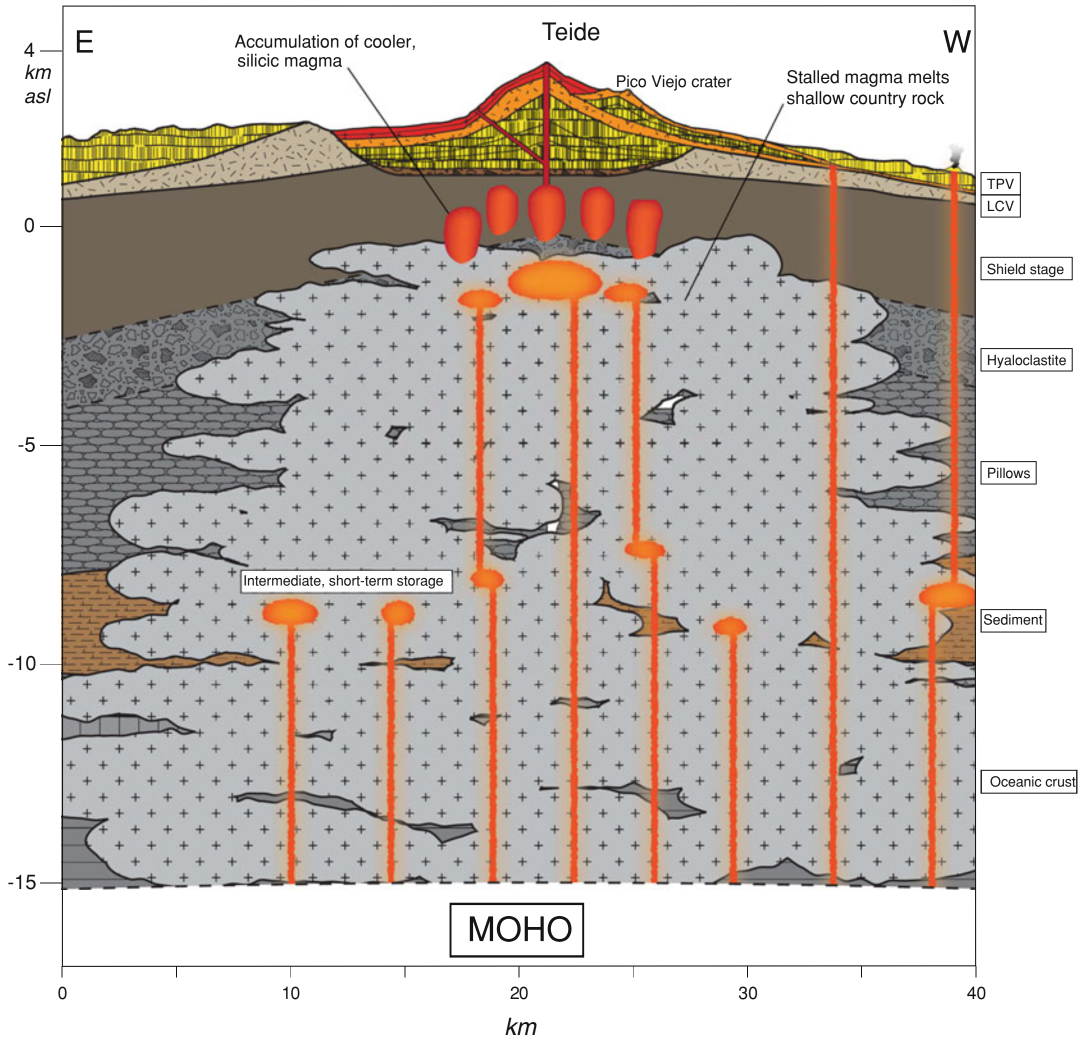


Fig. 10.9 Interpretative East–West cross-section of the current plumbing system of Tenerife (1.8 × vertical exaggeration). Teide–Pico Viejo deposits are colour-coded after compositional group. Note the greater degree of differentiation up-section. Deep island core and ocean crust lithology are represented in this sketch for orientation, but may in fact have been largely reworked by Tenerife's igneous activity since Miocene times. Included is information from the following publications: crustal structure, Krastel and Schmincke (2002); seamount sequence, Staudigel and Schmincke (1984); Teide–Pico Viejo and underlying units, Carracedo et al. (2007); height of landslide breccia, Márquez et al. (2008); inverse geothermal gradient, Annen and Sparks (2002). Lower crustal/upper mantle as the main crystallisation level has been invoked by multiple workers (Ablay et al. 1998; Hill et al. 2002; Spera and Bohrson 2004). In the Canary Islands specifically, intermediate levels of short-term magma residence were inferred from the re-equilibration of CO_2-inclusions in mineral phases (Klügel et al. 2005b; Galipp et al. 2006; Longpré et al. 2008). Underplating of hot, mafic material underneath the central Teide–Pico Viejo complex may cause formation of crustal melt pockets that are sometimes decoupled from the juvenile material providing the heat (see text for details)

applicable, since the lack of a common diffusive interface between magma and assimilant will preclude the uptake of crustal melts into resident magma. In other words, while fractional crystallisation is necessarily associated with the liquid magma, crustal melting may occur in the absence of direct contact with the heat-providing magma.

Because AFC processes and assimilant variability are both insufficient to explain the composition of phase 7 of the Montaña Blanca eruption in full, Wiesmaier et al. (2012) suggested that this lava is the product of a >98 % melt of pre-Teide nepheline syenite with very little juvenile material directly involved. All other phonolites and less differentiated lavas can be derived from juvenile mafic magma by various degrees of assimilation and fractional crystallisation. Direct mixing between mantle and crustal melts is also a possibility and may have modified some samples considerably (see also Chap. 11).

10.6 Petrogenesis at Teide–Pico Viejo

In the terminal stage of the pre-Teide Las Cañadas Volcano, the caldera-forming Diego Hernández phase was accompanied by the Icod landslide, which unroofed the junction of the two active rift zones and probably caused accelerated ascent of mafic magma from depth (cf. Longpré et al. 2008, 2009). This led to renewed and abundant mafic activity (Carracedo et al. 2007), and resulted in the "old" Teide eruptions ($\sim$200–100 ka), which were basanitic in composition. At this stage, older felsic intrusive material was not subjected to large-scale remelting. This may be because mafic eruptions in the Canaries are known to ascend swiftly via dyke systems (rift zones) with little to no residence time at shallow depth (cf. Klügel et al. 2005a; Stroncik et al. 2009; Troll et al. 2012) and because the magma supply may have been strong directly after the landslide, 'flushing' the system with mafic melt (e.g., Longpré et al. 2009; Manconi et al. 2009).

The increasing portion of crustal melts involved in the formation of higher differentiated lavas, all younger than 15–30 ka, indicates that at some point during the Teide–Pico Viejo history, felsic country rock began to be recycled to a significant degree. This was probably triggered by an increase in residence time of magma at shallow crustal levels. A potential explanation for this could be density filtering due to the increasing load exerted by the growing Teide–Pico Viejo edifice (cf. Pinel and Jaupart 2000) or, alternatively, the formation of 'density barriers' of partially molten and thus less dense felsic country rock that causes denser mafic magma to become neutrally buoyant (Huppert and Sparks 1988). The resulting underplating of mafic melts would have steepened the geothermal gradient and thus helped to eventually provide the energy for the wholesale-melting of the country rock (Fig. 10.9), cf. Annen and Sparks (2002).

The onset of crustal assimilation must have been progressive with the initial and relatively little contaminated transitional lavas erupted at around 30 ka, i.e., before the first felsic lavas appeared. The culmination of felsic activity at Teide took place with the eruption of high $^{87}Sr/^{86}Sr$ deposits around 2,000 years ago (Montaña Blanca and El Boquerón). According to EC-AFC modelling, the amount of pre-Teide felsic assimilant in these rather recent lavas is quite large. This implies that juvenile mafic magmas act as a heat source at depth to melt country rock, but are not always directly in contact with this newly forming crustal melt, or are unable to mix with it (Fig. 10.9). New, largely autonomous pockets of felsic magma are thus thought to be involved in the eruption of recent Teide phonolite.

Compositional bimodality has been demonstrated to exist in the case of Teide–Pico Viejo. The most primitive compositions evolve towards intermediate levels mainly by means of fractional crystallisation and variable, but small degrees of assimilation. In turn, highly differentiated magma broadly formed by AFC processes or by wholesale melting of felsic country rock and incomplete mixing. The observed contrast in differentiation processes between mafic and felsic lavas explains the bimodality and the temporal sequence of erupted lavas in the Teide–Pico Viejo succession and thus allows to establish a temporally, compositionally and geographically consistent model for the nature of phonolite volcanism on recent Tenerife.

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