9 Timing, Distribution and Petrological Evolution of the Teide-Pico Viejo Volcanic Complex

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Abstract

Several cycles of initially mafic to progressively felsic activity have given rise to large volume felsic deposits on Tenerife that serve as prime examples of pronounced magmatic differentiation in an ocean island setting. The Teide–Pico Viejo succession is the most recent of these cycles to show a systematic evolution from initially basanitic to phonolitic eruptions. Basanite lava flows bear olivine, pyroxene and occasionally plagioclase, while phonolites mainly display alkali feldspar with subordinate pyroxene, amphibole, biotite and oxides. Three groups of eruptives can be discerned based on their trace element composition: (1) Mafic lavas that show typical OIB signatures, (2) Transitional lavas, which are enriched in incompatible trace elements but may be depleted in Ba and Sr and (3) Phonolites, which are more enriched in incompatible trace elements, but show the strongest negative Ba and Sr anomalies. Linking the spatio-chronological distribution of eruptions with these compositional groups shows a progressive migration of mafic activity from the outskirts of the rift zones towards the central complex over the last 30 ka. The arrival of mafic activity at the central complex coincided with the onset of more evolved eruptions at Teide, thought to be triggered

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by mafic underplating. The distribution of mafic activity at the surface may thus be related to the volume of mafic underplating beneath the volcanic edifice at a given time.

9.1 Introduction

Magmatic differentiation is the modification of a magma's composition from its original primary make up. Primary magmas are melts that are assumed to have been generated by equilibrium partial melting of mantle rocks. As such, they can show certain variability in their composition, depending on mantle lithology and degree of partial melting involved. However, lava and intrusive rocks, which represent solidified magma, span a much wider compositional range. This implies that primary magmas are—more often than not—overprinted by processes that change their composition subsequent to their initial formation in the mantle.

The Teide–Pico Viejo succession represents a unique opportunity to investigate magmatic differentiation and the resulting felsic rock suites, in a young and very accessible ocean island setting. The Canary Islands form on top of slow-moving, thick oceanic lithosphere and show a relatively low magma-supply rate, only about one-tenth of that of the Hawaiian Islands (Sleep 1990). This increases the residence time of magma in the oceanic crust and the island edifices and results in cooling, crystallisation, magmatic differentiation and magma mixing. In contrast, highly productive hotspot settings, such as Hawaii, allow only for relatively short intervals of magma residence in the crust and thus reflect processes at greater depth, i.e. in the mantle. As a result, felsic material is nearly absent in the hotspot type-locality Hawaii, whereas large volumes of strongly differentiated, felsic rocks abound in the Canary Islands (e.g., Fúster et al. 1968; Schmincke 1969, 1976; Ridley 1970) and must represent the products of large-scale and voluminous magmatic differentiation.

The degree of differentiation that magma of a given volcano may reach directly influences that volcano's hazard potential. Differentiation generally increases the silica content of magma and so governs whether an eruption will be a comparatively passive outpouring of lava or, in contrast, a large cataclysmic explosion that may ravage proximal and distal (e.g., populated) territories. This is because silica increases the polymerisation in magma and can raise its viscosity by orders of magnitude (e.g., Hess and Dingwell 1996). Such high viscosity of e.g., rhyolitic or phonolitic magma is one of the fundamental drivers of explosive volcanism, because only high viscosity magma can be fragmented on a large scale during eruption (Webb and Dingwell 1990; Dingwell 1996), a phenomenon which is promoted at high silica concentration.

Two main processes of magmatic differentiation are known to change the composition of magma towards high silica values: fractional crystallisation and assimilation (e.g., DePaolo 1981). Fractional crystallisation, on one hand, is the commonly assumed way of magma evolution on cooling, whereby newly formed crystals are removed from the melt, for example by gravitational settling (e.g., Bowen 1928; Wager and Brown 1967). Because the most common magmatic crystals are combined of only a small number of components assembled in varying proportions, they deplete the remaining magmatic liquid in the elements they take up to grow, while the unused components become enriched in the magma. As a result, differentiated magma (often also called 'evolved') experiences a change in chemical composition, which usually manifests in an increased SiO_2 concentration associated with high concentrations of large ion lithophile elements such as Rb, Na and K. The magma becomes more felsic (Fig. 9.1).

Assimilation, on the other hand, describes the reaction of hot magma with the surrounding country rock that forms the boundary walls of a magma reservoir. Any magma that cleaves through the Earth's crust is likely to encounter a

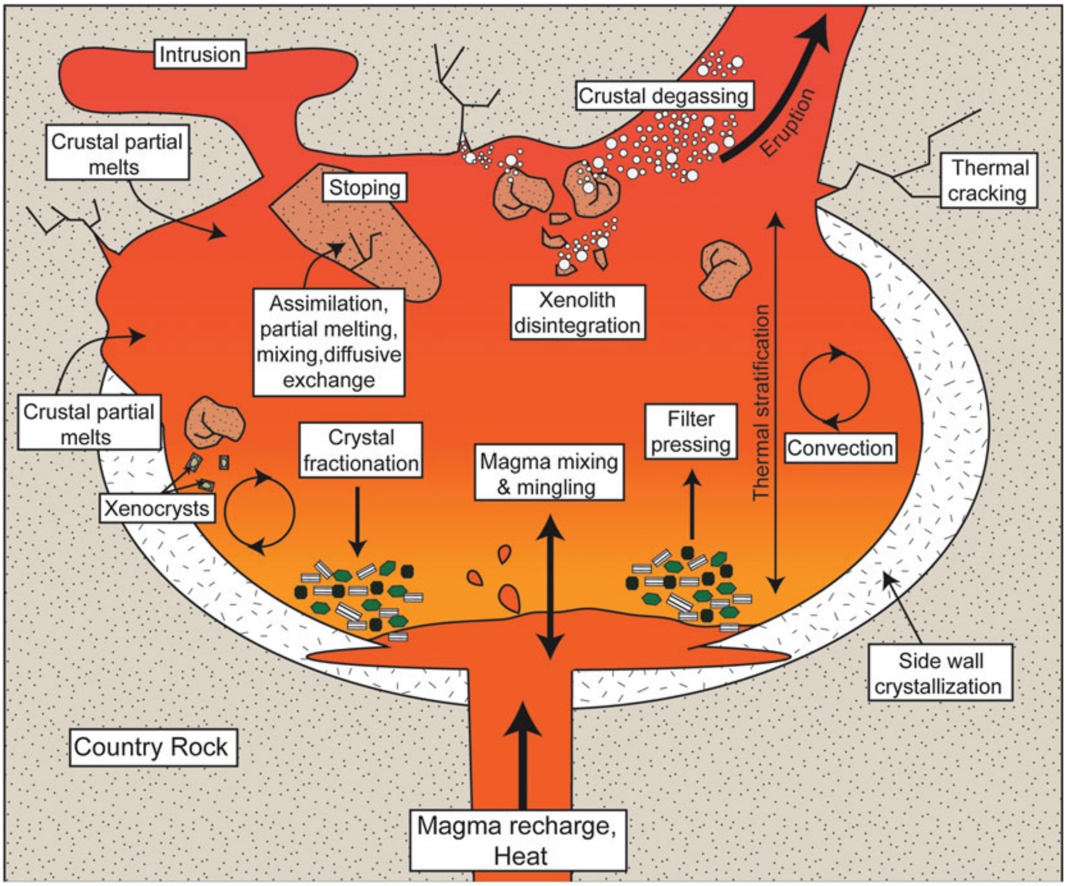

Fig. 9.1 Idealised sketch of differentiation processes that may occur in a crustal magma chamber (courtesy of F. Deegan)

variety of rock types that the crust is built of. At deep levels below Tenerife, the ultramafic rocks of the mantle grade into a sequence of rocks that are typical for the oceanic crust (e.g., gabbros, dykes and pillow lavas). Moreover, at shallow levels, the rocks from the volcanic edifice itself have to be passed by newly ascending magma. How intensely the ascending magma can be changed in composition by assimilation depends on three factors: the solidus of the wall rock, the compositional gradient between wall rock and magma, and the temperature of both magma and wall rock, i.e. the amount of energy released by the cooling magma that leads to melting of wall rock. The solidus of different wall rock lithologies varies strongly with their composition and the fusion enthalpies of their mineralogy, but most wall rocks will become partially unstable when exposed to temperatures of 1,200–1,300 °C (cf. Spera and Bohrson 2001). Wall rock compositions that are distinct from the magma may result in strong disequilibrium kinetic reactions that dissolve wall rock minerals prior to melting (e.g., Watson 1982; Deegan et al. 2010, 2012). Finally, the volume and temperature of magma versus that of the wall rock delimits the energy available for consumption of the wall rock. It follows that the type and the amount of rock that exists at depth beneath a volcano may have considerable influence on magma type and, hence, on its eruptive behaviour. This influence has to be determined for each volcano individually (Fig. 9.1).

The two differentiation processes, assimilation and fractional crystallisation, are complemented by magma mixing, which describes the homogenisation of two melts of different composition to produce a new magma of hybrid composition, e.g., mixed silica concentration (e.g., McBirney 1980). Less frequently observed in nature is liquid immiscibility, i.e. the unmixing of components from a multi-component silicate melt (e.g., Best 2003).

Tenerife has displayed several cycles of mafic to increasingly felsic eruptions throughout the last 2 Ma, indicating a systematic evolution of the magmatic system with pronounced magmatic differentiation being at work in Tenerife's interior. Overall, Tenerife shows a marked increase in volume of erupted felsic material throughout its subaerial history of about 12 Ma, with the post-shield Las Cañadas Volcano (<3.5 Ma) having developed towards very large volume cataclysmic felsic eruptions (e.g., Ancochea et al. 1999). Comparable to the previous cycles of the Las Cañadas Volcano, Tenerife's youngest eruptive succession, the products of Teide–Pico Viejo show a complete sequence from early mafic eruptions to progressively more differentiated compositions of the alkaline series up to phonolites. Because of their young age and a lack of overlying units to bury them, it has been possible to document the stratigraphy, age and compositional variation of this lava succession to superb detail (Rodríguez-Badiola et al. 2006; Carracedo et al. 2007, 2008). The age and stratigraphical constraints used here are presented in Chap. 7 and further information on the quantification of differentiation processes can be found in Chap. 10.

9.2 The Significance of Felsic Volcanism in Ocean Islands

In a setting devoid of large regional tectonic influences and thick continental crust, crystal fractionation had commonly been proposed as the principal differentiation process forming abundant felsic volcanic material (e.g., Cann 1968; Schmincke 1969; Clague 1978; Garcia et al. 1986; Thompson et al. 2001). This is at odds, however, with the frequently observed bimodality of lava compositions (Chayes 1963). Early investigations of the compositional bimodality of volcanic matter [the "Bunsen-Daly Gap", after Bunsen (1851) and Daly (1925) and later expanded on by Barth et al. (1939)] were largely concerned with the discussion of whether or not a gap actually existed between mafic and felsic end-member compositions (e.g., Chayes 1963; Baker 1968; Cann 1968). This manifested itself in an argument about potential sample bias and suggestions for more detailed geological work (Harris 1963; Baker 1968; Cann 1968). As a result, Schmincke (1969) identified a Bunsen-Daly gap in Gran Canaria, as did Ridley (1970) for erupted compositions in Tenerife. Fúster et al. (1968) suggested its presence in Fuerteventura, La Gomera, El Hierro as well as Lanzarote eruptives. The Bunsen–Daly gap was commonly argued to be a consequence of fractional crystallisation (e.g., Cann 1968; Schmincke 1969; Clague 1978; Garcia et al. 1986; Thompson et al. 2001), but the potential influences of partial melting were also suggested (Chayes 1977).

In continental epeirogenic settings, arguably a tectonically more complex environment compared to ocean islands, strong bimodalities also exist among the compositions of erupted material. For example, in the east African Gregory Rift Valley the eruption of Miocene flood basalts was rapidly followed by large volume plateau phonolites (Baker et al. 1971). Estimated ratios of felsic to mafic eruption volumes range between roughly 0.5 and 1.5 for between the Miocene to Holocene epochs, showing an overabundance of felsic material compared to what is expected from pure fractional crystallisation scenarios (Williams 1972). The lack of intermediate composition lavas was invoked to have originated either from partial melting of upper mantle by either a reduction in pressure by crustal upheaval or, alternatively, from an upper mantle, which is hotter and thus more susceptible to partial melting (Williams 1970). Hypotheses on the origin of Kenyan phonolites that invoked partial melting of upper mantle material were criticised by Lippard (1973). Due to the trace element patterns of these highly differentiated phonolites, it was argued that they cannot have formed by mere partial melting of mantle lithologies.

Explanations for this bimodality started to diversify considerably in the 1980s. Crystal fractionation models were modified to allow for large crystal loads that restrain convection and induce bimodality in erupted compositions (e.g., Marsh 1981; Brophy 1991 and references therein). Bailey (1987) suggested an upper mantle origin for trachytic melts, while Bonnefoi et al. (1995) invoked a model of critical cooling dynamics to be responsible for observed compositional relationships. More recently, assimilation of country rock has gained renewed momentum in differentiation models for magmas erupted in oceanic islands and is increasingly recognised (e.g., Thirlwall et al. 1997; Bohrson and Reid 1998; Garcia et al. 1998; O'Hara 1998; Harris et al. 2000; Troll and Schmincke 2002).

In Tenerife, too, fractional crystallisation was long considered the main differentiation process for the formation of felsic material (Wolff 1983; Wolff and Storey 1984). Relatively recently, recycling (i.e. partial or bulk melting) of rocks from within the island has been suggested to contribute to the evolution of felsic magmas in Tenerife (Wolff and Palacz 1989; Wolff et al. 2000), which would explain the large volumes of felsic material in some of the successions. However, the Teide–Pico Viejo stratovolcano was suggested to have mainly formed by fractional crystallisation with only minor assimilation of zeolite and/or hydrothermally altered material to explain deviations in trace element concentration from the fractionation trend (Ablay et al. 1998). Until then, systematic studies of the isotopic composition of Teide–Pico Viejo lavas to clarify the extent of assimilation at work had not been attempted.

9.3 Petrological History of Tenerife Island Prior to Teide Formation

Three overlapping shield volcanoes (Roque Del Conde, Teno and Anaga) formed between 11.9 and 4 Ma and constitute the subaerial foundation of Tenerife (Carracedo 1979; Ancochea et al. 1990; Thirlwall et al. 2000; Guillou et al. 2004; Paris et al. 2005; Walter et al. 2005). The first shield to emerge was the central shield, or Roque Del Conde, followed by the peripheral shields Teno and Anaga in the northwest and northeast, respectively.

As is typical for shield volcanoes, mainly mafic volcanism occurred, i.e. basanites, picrobasalts and alkali basalts. Picrobasalts are ankaramites with 40–60 % phenocrysts, mainly pyroxene and olivine, which are very likely of accumulative origin. All other volcanic rocks in Tenerife remain mostly below 20 % phenocrysts. Up-section in the stratigraphy of each of the three shield volcanoes, minor amounts of trachytic and phonolitic dykes, plugs and lavas and occasionally pyroclastic deposits are found (e.g., Walter et al. 2005; Longpré et al. 2009).

After the peripheral shields, Teno and Anaga, went extinct, the volcanic activity returned to the centre of the island at around 3.5 Ma, to build the Las Cañadas Volcano on top of the Roque Del Conde shield (Martí et al. 1994; Ancochea et al. 1999). Eruptive episodes in the Las Cañadas Volcano tended from scattered eruptive activity to distinct cycles of mafic to felsic eruptions, indicating the development of a central system of felsic magma chambers. The Las Cañadas Volcano consists of a complex Lower Group formation that comprises multiple and scattered eruptive centres and a three-cycle Upper Group, of which each cycle broadly evolved from subordinate, primitive effusion to large-volume felsic eruptions. The 2nd and 3rd cycle of the Upper Group culminated in the caldera-forming ignimbrite formations of Granadilla (~570 ka) and Abrigo (~180 ka), respectively (e.g., Wolff 1983; Martí et al. 1994, 1997; Bryan et al. 2000; Brown et al. 2003; Brown and Branney 2004; Edgar et al. 2007).

In the terminal stage of the Las Cañadas Volcano, the Diego Hernández Formation, a spectacular caldera-forming sequence, was erupted from various phonolite magma chambers, often, it seems, triggered by mafic recharge (e.g., Wolff 1983; Bryan et al. 1998; Wolff et al. 2000). For example, in the Poris member of the

Diego Hernández Formation, four types of magma have been distinguished; a high-Zr phonolite (most abundant), a low-Zr phonolite with higher MgO that is often intermingled with a tephriphonolite and, finally, a phonotephrite. The phonolite pumices contain alkali feldspar, biotite, sodic salite and Fe–Ti oxides, but in the high-Zr phonolites titanite also occurs. Intermediate composition pumices contain kaersutite, plagioclase, low-Na salite and Fe–Ti oxides, whereas the most mafic magma contains olivine, titanaugite and calcic plagioclase (Edgar et al. 2002). The large variability in lithic blocks contained in pyroclastic deposits of the Las Cañadas Volcano and the large volumes of the terminal members of individual Las Cañadas cycles (e.g., Granadilla, Abrigo ignimbrites) testify to the disruptive and catastrophic nature of these mixed eruptions, which most likely formed sub-circular caldera depressions (cf. Edgar et al. 2007). The Abrigo event, the last phase of cataclysmic eruptions of the Las Cañadas system, was probably closely associated with the ~200–180 ka Icod landslide (Watts and Masson 1995; Carracedo 1999; Carracedo et al. 2007; Márquez et al. 2008). The 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), but have probably been largely mass-wasted by the landslide. The Icod landslide relieved the magmatic plumbing system in the centre of the island of a large volume of overburden, unroofing the junction of the three-armed rift zone system and very likely, resetting the system to the eruption of mafic materials such as picrites and ankaramites (cf. Longpré et al. 2009; Manconi et al. 2009). Of the three rifts, the northwest and northeast arms are currently active and extend from underneath Teide–Pico Viejo volcano into the Teno and Anaga massifs (Carracedo et al. 2007, 2011; Chaps. 4 and 5). These rifts control the overall structure of Tenerife and show dominantly mafic volcanism in the form of basanites to rarer phonotephrites that erupt along elongated arrays of monogenetic cones (Chap. 4). The Icod landslide then triggered extensive amounts of mafic eruptions, as evidenced by the horizontal sections obtained from various *galerías* that penetrate the infill sequence (Chap. 7). The uncapping of the rift system marked the onset of a new cycle of eruptive activity in Tenerife by promoting rapid ascent of new and deep mafic magma into the collapse scar and thus initialising the construction of Teide–Pico Viejo central volcanic complex. Even more regular in its evolution from mafic to highly differentiated lavas than the previous cycles, the formation of Teide–Pico Viejo central complex concentrates Tenerife's non-rift activity into a single central and felsic edifice.

9.4 Petrological Description of the Teide–Pico Viejo Succession

The petrological traits of Teide–Pico Viejo have been the focus of several research publications (Fúster et al. 1968; Araña et al. 1989a, b; Ablay et al. 1998; Ablay and Marti 2000; Rodríguez-Badiola et al. 2006). Here, the main petrological features of the Teide–Pico Viejo succession are summarised, following the latest account of Rodríguez-Badiola et al. (2006).

9.4.1 Mafic Lavas

9.4.1.1 Basanites and Tephrites

Basanites are highly abundant in all volcanic sequences in Tenerife, both in the Teide–Pico Viejo succession as initial collapse fill and as the main constituent of the northeast and northwest rift zones. The initial mafic eruptions of Teide–Pico Viejo are petrographically indistinguishable from the synchronous rift zone eruptions. These early eruptions are the most primitive lavas found in the Teide–Pico Viejo succession and comprise basaltic rocks that bear olivine, clinopyroxene (titanaugite) and magnetite in variable proportions (locally reaching ankaramitic character) along with scarce plagioclase in a fine-grained groundmass. The matrix varies from micro- to hypocrystalline, is sometimes vesicular, and

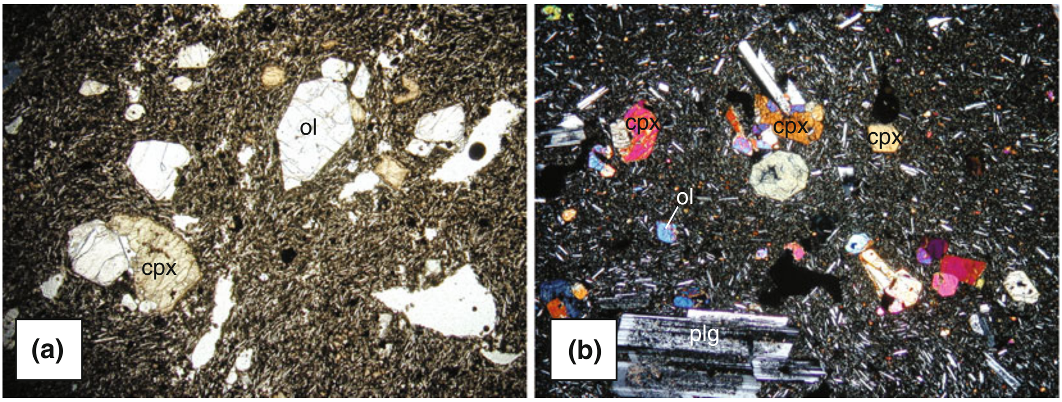

Fig. 9.2 **a** Olivine pyroxene basalt. Phenocrysts of titanaugite (*cpx*), olivine (*ol*) and opaque oxides in a hypocrystalline, mafic matrix (PP; 10×). **b** Olivine pyroxene basalt with plagioclase. Phenocrysts of augite (*cpx*), olivine (*ol*), sieve-textured plagioclase (plag) and opaque oxides in a hypocrystalline matrix with plagioclase microlites. (XP; 10×)

usually consists of laths of plagioclase and microlites of clinopyroxene, olivine and Fe–Ti oxides, but can also be more glassy locally (Fig. 9.2). This group also includes some olivine, clinopyroxene and plagioclase basalts with abundant plagioclase, indicating a slightly higher degree of differentiation within the basanite field, although still maintaining an overall mafic character.

9.4.1.2 Plagioclase Basalts

This group effectively combines all pāhoehoe flows of the Teide–Pico Viejo succession. These lavas are characterised by their long, tabular and thin plagioclase phenocrysts with frequent sieve textures, and they carry subordinate olivine and clinopyroxene, supported by a hypocrystalline and vesicular matrix. A variation of this type of lava is micro-plagioclase basalt, in which feldspar crystals of limited size are embedded in a hypocrystalline matrix of feldspathic composition (Fig. 9.3). On the surface, this lava type is only found within the initial flow sequence of Pico Viejo, but subterraneously this type abounds in the interior of *galerías* (e.g., Galería Salto del Frontón).

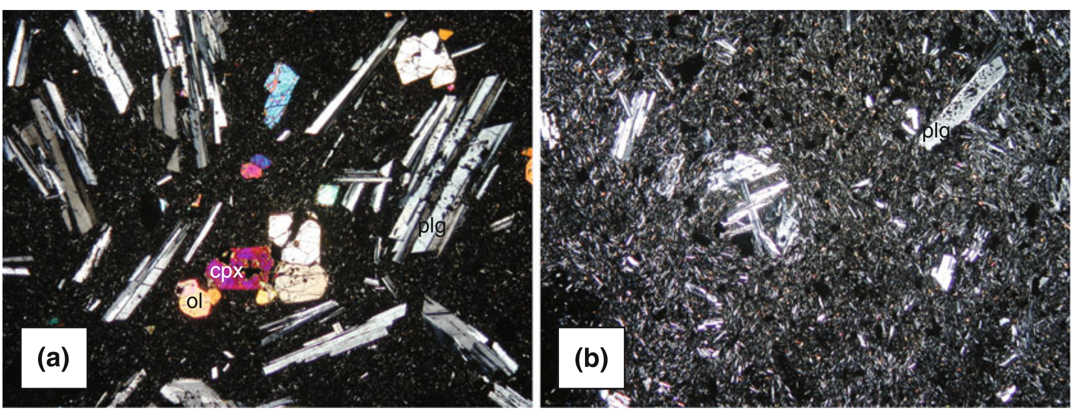

Fig. 9.3 **a** Plagioclase basalt from pāhoehoe flow with predominant plagioclase phenocrysts, and less augite and olivine in a hypocrystalline matrix (XP; 10×). **b** Micro-plagioclase basalt. Mesocrystals of plagioclase dominate over mafic minerals in a feldspathic matrix (XP; 10×)

9.4.1.3 Trachybasalts

This group includes hawaiites and potassic trachybasalts and was recognised in Tenerife by Fúster et al. (1968). Typical trachybasalts are characterised by abundant plagioclase phenocrysts of intermediate composition together with slightly sodic augite, oxides and subordinate olivine, suspended in a hypocrystalline matrix (Fig. 9.4). They are mainly found in *galerías*, for example in the Galería Salto del Frontón, where they occupy an extended part of the galería wall (500–1,000 m) and in the lavas of *Bocas de Dña. María*, a satellite vent of Teide. In some examples of this lava type, amphibole is present as stable phenocryst phase and these lavas may be intercalated with more evolved ones such as the intermediate Pico Viejo lavas that flowed south.

9.4.2 Transitional Lavas

Between 30 and 20 ka, the Teide–Pico Viejo edifice and its flank vents began to erupt more differentiated material (Carracedo et al. 2007). These lavas fall into the compositional fields of phonotephrite and tephriphonolite in the total alkali versus silica (TAS) diagram and show a large diversity in alkali concentration and petrography. At the mafic end of this group, alkaline feldspar (anorthoclase) occurs together with sodic augite, oxides and amphibole crystals with oxidation rims (Fig. 9.5). Often relict olivine is present. The more evolved lavas of this group show anorthoclase crystals together with euhedral amphibole, which indicates volatile saturation in the trachytic matrix at this stage of differentiation (Fig. 9.6). These lavas occur between the mafic and the felsic groupings in the stratigraphy of Teide–Pico Viejo central complex and, although rarely, are also found in the rifts.

9.4.3 Felsic Lavas

The highest degree of differentiation so far reached in the Teide alkaline series was the eruption of phonolite, the dominant lava composition of the last 20 kyr at Teide complex. These phonolites are occasionally intercalated in the stratigraphy with tephriphonolites and sometimes approach trachytic composition, as in the case of some domes of the Montaña Blanca sequence (Ablay et al. 1998). Typically, the phonolites contain alkaline feldspar (anorthoclase to sanidine), scarce aegirine-augite and alkaline amphibole, biotite and oxides embedded in a frequently glassy and often flow-banded matrix (Fig. 9.7).

During the progressive evolution of Teide–Pico Viejo from an initially mafic character to a

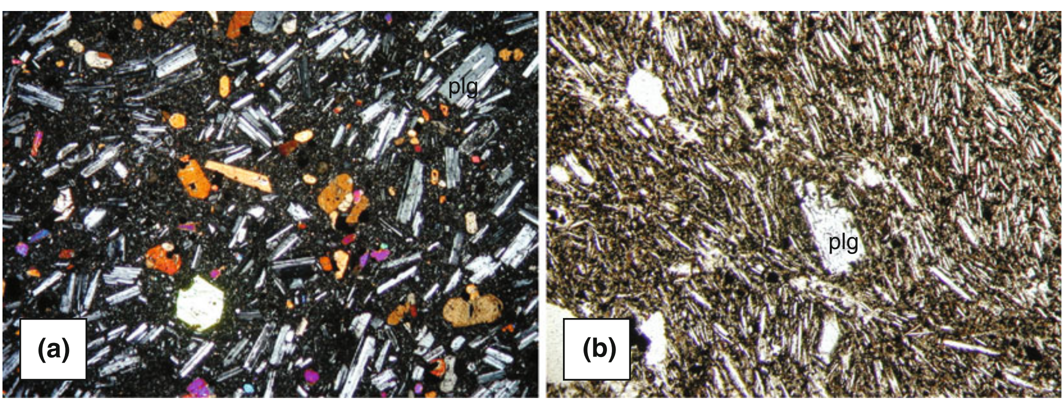

Fig. 9.4 **a** Trachybasalt from the Galería Salto del Frontón (560 m), containing frequent plagioclase of sodic composition together with augite and subordinate olivine in a hypocrystalline matrix. (XP; 10×). **b** Aphyric basanite bearing mesocrystals of plagioclase with scarce mafic microlites in a felsic matrix. (PP; 10×)

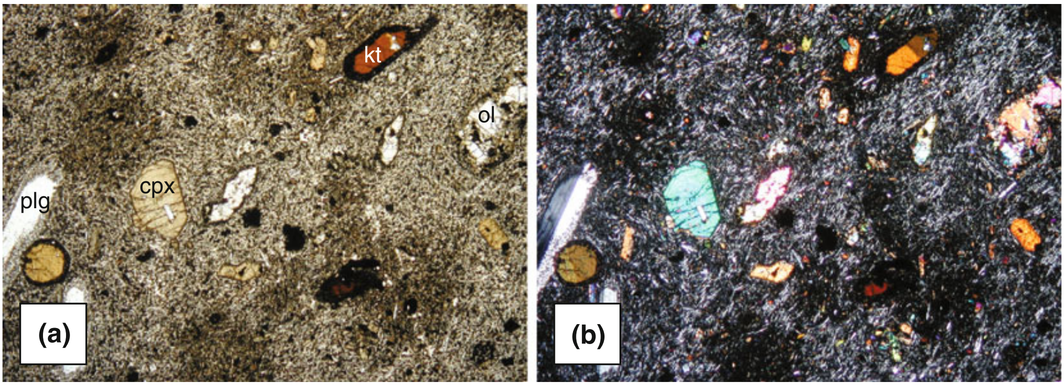

Fig. 9.5 Mafic tephriphonolite from the Galería Salto del Frontón (2,200 m), with plagioclase phenocrysts, titanaugite, Ti-amphibole with oxidation rims (kaersutite, kt), oxides and relict olivine in a hypocrystalline matrix with indications of immiscibility (**a** PP & **b** XP; 10×)

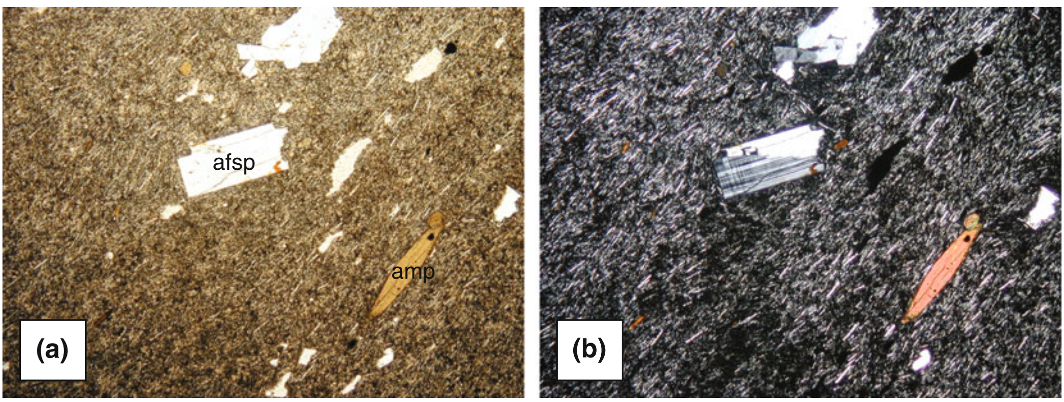

Fig. 9.6 Amphibole-bearing phonotephrite from the Galería Salto del Frontón (400 m). Anorthoclase phenocrysts (*afsp*) and ampibole in a microcrystalline matrix displaying flow lineations. (**a** PP & **b** XP; 10×)

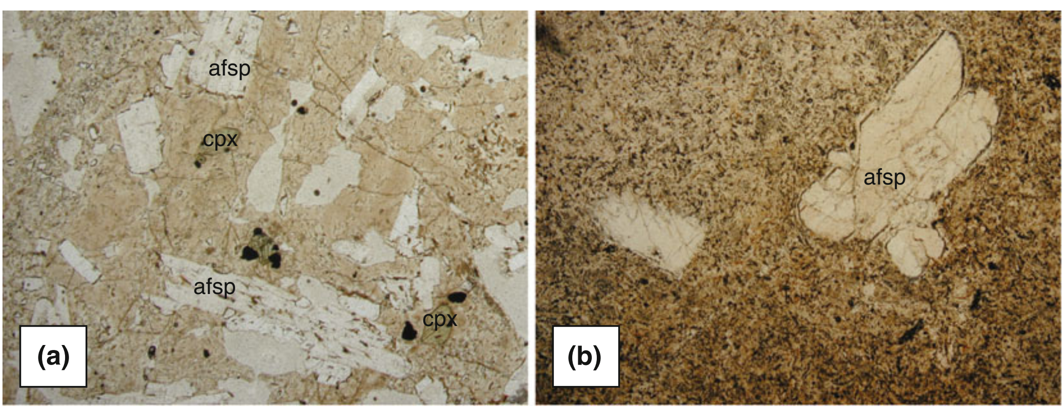

Fig. 9.7 **a** Lavas Negras, the product of the last eruption from the peak of Teide. Phenocrysts of anorthoclase and sanidine, aegirine-augite and scarce opaques in a hypocrystalline matrix. **b** Felsic phonolite from the Galería Salto del Frontón (360 m) showing anorthoclase and sanidine crystals in a trachytic matrix. (PP; 10×)

highly differentiated central volcano, the adjacent rift zones continued to produce mafic activity, with on average one eruption per century. In the boundary zone between the rift zones and the central complex, magma mixing of basanite (from the rift zone) and phonolite (from the central complex) frequently occurred (Araña et al. 1994; Wiesmaier et al. 2011, see Chap. 11), indicating that interaction between the two regimes is common. Ultimately, Teide–Pico Viejo has been constructed by initially mafic magma fed into the junction of the two rift zones (~200–40 ka) and has only subsequently developed highly differentiated compositions (~40–0 ka), while the rifts continued with mafic activity. Both regimes, rift zone and central volcano, are thus closely related and may be regarded as a single larger system.

9.5 Trace Element Characterisation of the Teide–Pico Viejo Succession

In order to compare the many lavas of one succession, it is useful to group those lavas sharing common geochemical traits. This is usually done in a TAS diagram (Le Bas et al. 1986). Rocks from the Teide–Pico Viejo succession plot as an alkaline trend from basanites to phonolites with some excursions into the trachytic series. The dataset comprises 97 % of the known eruptions of the last 200 ka, with only one sample per unit presented to avoid over-representation (Fig. 9.8).

At a single volcanic centre, additional information may also be gathered by grouping the eruptive deposits according to their trace element characteristics. Here, the Teide–Pico Viejo lavas are categorised by parallel trace element patterns, i.e. trends that do not cross-cut each other. Parallel patterns indicate combinations of trace element ratios that are related and thus represent similar geochemical histories. Positive or negative anomalies in the elements Pb, Ba and Sr further characterise the Teide–Pico Viejo lavas (Fig. 9.9). Three groups can be inferred from the trace element patterns, which we label the mafic, transitional and felsic lavas. Throughout this and the following chapter, the terms mafic, transitional and felsic are used in the context of the trace element classification devised below.

The mafic lavas (*yellow squares*) comprise all basanites and tephrites from the rift zones, one foidite, one basaltic trachyandesite and several intra-caldera and Teide–Pico Viejo phonotephrites and trachybasalts. They possess a negative Pb anomaly relative to the neighbouring elements in a multielement variation diagram. The mafic lavas are the most abundant (n = 40).

The transitional lavas (orange diamonds) range from trachyandesites to trachyte and from tephriphonolites to phonolites. These samples show positive Pb anomalies, negative Sr anomalies and a small to absent negative Ba anomaly. The transitional lavas (n = 10) erupted from the margins of Teide–Pico Viejo complex or vents inside the Las Cañadas Caldera and frequently define the compositional boundary between the rift zones and central complex.

The felsic lavas (red triangles) are exclusively comprised of phonolites that erupted from Teide–Pico Viejo or the flank vents of the volcano. The felsic lavas (n = 12) include, but are not limited to, Montaña Blanca, Roques Blancos and the last eruption from Teide's central vent (Lavas Negras, 1,150 ± 140 years BP). They are defined by strongly negative anomalies in both Sr and Ba, with Sr always showing values <10 (normalised to primitive mantle).

Combining the trace element grouping with the TAS diagram, mafic lavas show a continuous trend towards transitional compositions, but with a decrease in variability of the alkali elements (Fig. 9.9). Transitional lavas appear much more scattered and comprise loosely grouped tephriphonolites, phonolites and trachytes. Felsic lavas define a trend at a steep angle to the classic differentiation trend established by the less evolved samples. Geographically, the vents of the three compositional groups display a concentric arrangement around the central volcano Teide (Fig. 9.10).

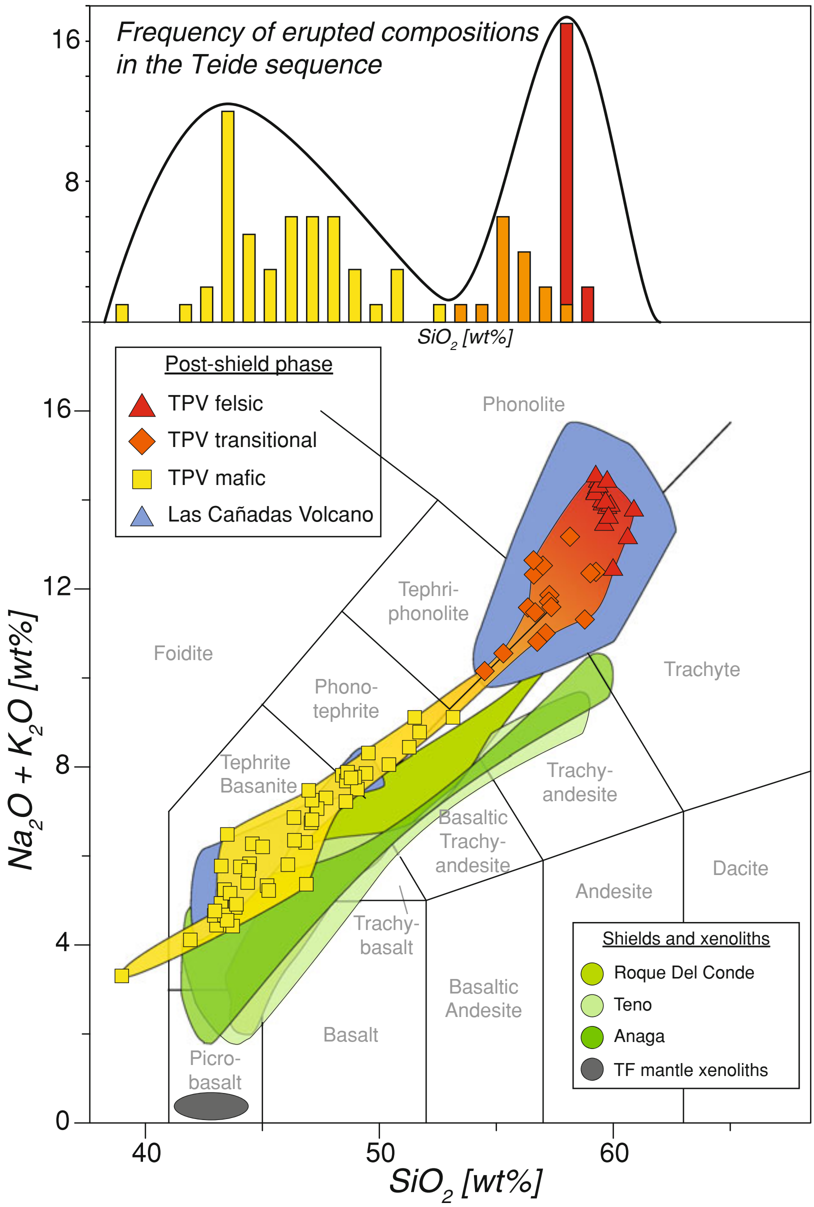

Fig. 9.8 Teide–Pico Viejo samples plotted on a total alkali versus silica diagram after Le Bas et al. (1986). Note the well-defined trend of the mafic lavas, the loose clustering of transitional lavas and the sub-vertical trend defined by the felsic group. Data from Rodríguez-Badiola et al. (2006), Thirlwall et al. (2000) and Neumann et al. (2002)

The strongly negative anomalies of Ba and Sr found in Teide felsic lavas were traditionally considered a hallmark of feldspar fractionation, the only mineral in these rocks to include these two cations in significant amounts. At Teide–Pico Viejo, this argument is seemingly supported by the fact that most of the differentiated lavas bear this mineral, so at first glance it appears that feldspar fractionation depleted Ba and Sr in Teide's phonolite magmas. Along these lines, Ablay et al. (1998) constructed a detailed model of fractional crystallisation,

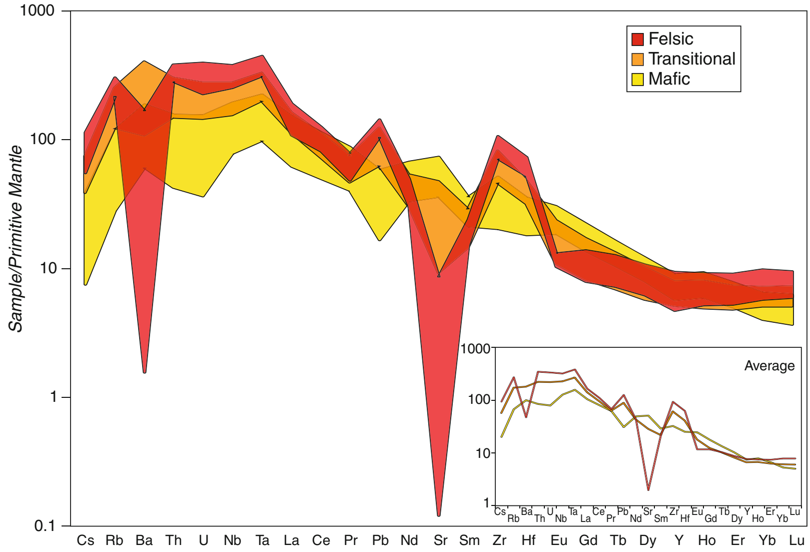

Fig. 9.9 Multi-element variation diagram (spiderdiagram) for post-collapse lavas of Tenerife, normalised to primitive mantle after McDonough and Sun (1995). *Inset* shows averages for each group. Note the enrichment of most incompatible elements with degree of differentiation. In turn, MREE and Sr, Ba and Eu become increasingly depleted

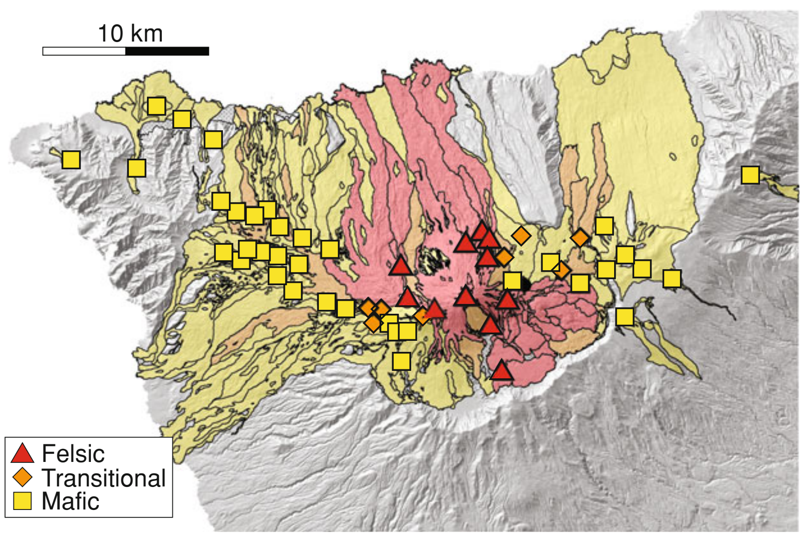

Fig. 9.10 Distribution of vents of the Teide–Pico Viejo succession in Tenerife. *Triangles* felsic lavas, *diamonds* transitional lavas, *squares* mafic lavas. The *black circle* indicates Montaña de los Conejos, an eruption for which whole-rock data is not available. Note the clustering of felsic lavas within the central complex. The mafic lavas define the rift zones, but also occur in the older products of the central complex. The transitional lavas fall into the geographical and chemical transition between the mafic and felsic regimes, i.e. the two rift zones and the central complex respectively

focussing on major and trace element data. As a result, they interpreted Teide phonolite lava to be a residual melt of around 12 % of the original mafic melt, the remaining 88 % having been removed from the magma by crystal separation. Disparities between natural and modelled trace element concentrations were explained by minor assimilation of zeolite or hydrothermally altered materials. End-member contaminant data were not presented nor were isotope data, which means that their interpretation can be tested by means of isotopic analyses (see Chap. 10).

9.6 Volumetric and Spatio-Chronological Characterisation of the Teide–Pico Viejo Succession

Tenerife is a mature volcanic island that underwent multiple mafic-to-felsic eruptive cycles in the post-shield Las Cañadas succession (e.g., Ancochea et al. 1999). The latest eruptive cycle of Teide–Pico Viejo thought to succeed Las Cañadas, has been volumetrically estimated at 160 km^3, divided into ~62 km^3 of initial fill in the collapse embayment (dominantly mafic), ~70 km^3 for the old Teide edifice (mafic to transitional), ~15 km^3 for Pico Viejo volcano (mafic to transitional), ~6.5 km^3 for Teide satellite vents (felsic) and ~0.7 km^3 for the final construction of the Teide stratocone (felsic) (Carracedo et al. 2007). Rift zone eruptives are estimated during Teide's construction period to be around 32 and 9 km^3 for the NWRZ and NERZ, respectively. The distinction between mafic, transitional and felsic lavas is not always clearly defined in these estimates, due to partial or complete burial of units older than 15 ka. It was possible, however, to constrain the volume of individual, more recent eruptions at Teide–Pico Viejo (<15 ka) (Fig. 9.11; Carracedo et al. 2008).

Eruption frequency appears to decline with degree of differentiation. Teide–Pico Viejo phonolites erupted seldom (~every 1,000 years), but with much larger volumes compared to the small, mafic rift zone eruptions that occured up to 10 times as often. Eruptive frequency of transitional lavas also appears to have declined over the last 15 ka and fall below mafic lavas in terms of total volume. The felsic lavas, in turn, volumetrically dominated over the last 15 ka. Considering the large volumes of mafic lavas that initially filled the collapse scar, transitional lavas are probably subordinate to both felsic and mafic lavas. The compositional bimodality of the lava flows is thus evident in both, eruptive frequency and estimates of erupted volume.

The distribution of eruptive activity through time offers further insight. Figure 9.12 is a diagram of vent location (longitude) versus the age of an eruption. There, the evolution of Teide–Pico Viejo from eruption of mafic to felsic lavas results in a present day shadow zone of exclusively felsic eruptions (red), in which no mafic material is transported to the surface. The activity in the rift zones, however, has migrated through time (diagonal arrows). A systematic shift in activity has taken place in both rift zones from the distal parts of the rift to the more proximal parts, closer to the perimeter of Teide–Pico Viejo complex, beginning at around 35 ka in the NERZ and at 20 ka in the NWRZ. At approximately the same time mafic activity 'arrived' at the central complex, the first transitional lavas (PT-INE) erupted from the complex.

Crustal recycling very likely occurred during the petrogenesis of these transitional and felsic lavas (see Chap. 10). The close spatial association of mafic activity in the proximal parts of the rift and the initial transitional material erupted may indicate that mafic magma became increasingly arrested and that underplating became a significant phenomenon at that point. Underplating is the main heat source for crustal recycling and occurs when magma reaches a level in the crust of equal or lower density, with the resulting neutral buoyancy causing it to stall (cf. Walker 1993). As magma would continue to be fed into the system from below into the centre of the island, such a lens of underplated magma may have caused a diversion of mafic magma, initially from the centre of the island to the outskirts of the rift zones. The subsequent inward-shift of mafic activity towards the central phonolitic volcano implies that from then on mafic magma may have started to pool underneath this low density phonolite barrier and potentially reactivated solidifying and semi-solid felsic magma chambers that had formed previously. Such an interaction of rift zone and central volcano has been documented for

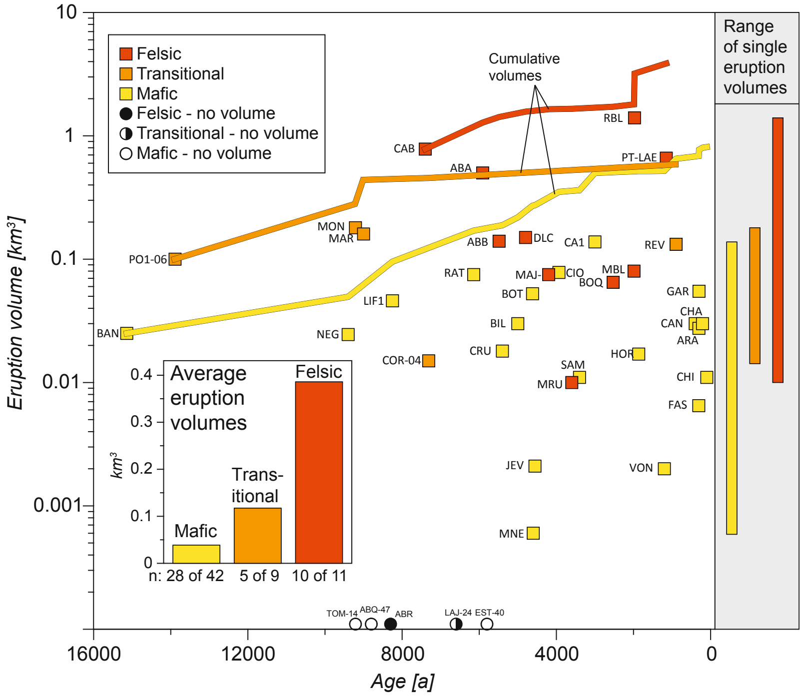

Fig. 9.11 Cumulative eruption volumes of the Teide–Pico Viejo succession of the last 15,000 years, grouped by composition. The inset shows the average eruption volumes of the three main groups, mafic, transitional and felsic lavas. Note how the degree of differentiation correlates with average and cumulative volumes. Mafic lavas have overtaken transitional compositions in cumulative volume due to their much higher eruptive frequency. Eruption volumes Carracedo et al. (2008), except for Montaña Blanca, which is from Ablay and Martí (2000)

example in the eruption of Montaña Reventada (Wiesmaier et al. 2011; see Chap. 11) and also manifests itself in the clustering of felsic and mixed eruptions along the projections of both the NERZ and NWRZ rift trends into the marginal areas of the central complex.

Based on the presented record, the future activity of Teide–Pico Viejo seems to be in slow decline. The record of explosive eruptions in the Teide–Pico Viejo succession alone is too ambiguous and with only a single explosive episode recorded, the statistics are inconclusive (see Chap. 13). However, the statistics could be interpreted in several ways, either as knell to more explosive activity, because one of the latest eruptions at Teide was sub-plinian (Ablay et al. 1995), or as the last gasp of a fading system. Teide–Pico Viejo may well thus indicate a consolidation of the Tenerife volcanic system towards lower magma production rates, but with a potential for development of small- to medium-scale explosive eruptions most likely from satellite vents around the central complex. Notably, the force and size of the Montaña Blanca eruption was considerably smaller than the large ignimbrite eruptions of the Pliocene Las Cañadas volcano. In contrast, the eruptive record of the last 1,000 years shows that mafic activity is scattered in comparison to the more localised earlier trends observed (Fig. 9.12). Apparently, the Teide phonolitic eruption has initiated a wider dispersal of volcanic activity (Fig. 9.12). For example, in the NERZ, mafic eruptions occurred again after a pause of nearly 10 ka and likewise in the NWRZ several historical eruptions occurred in the more distal parts of the rift, contrasting the previous trend that had converged towards the central volcano. This may be interpreted as a quasi-relaxation of the system, or as a new cycle of diversion of

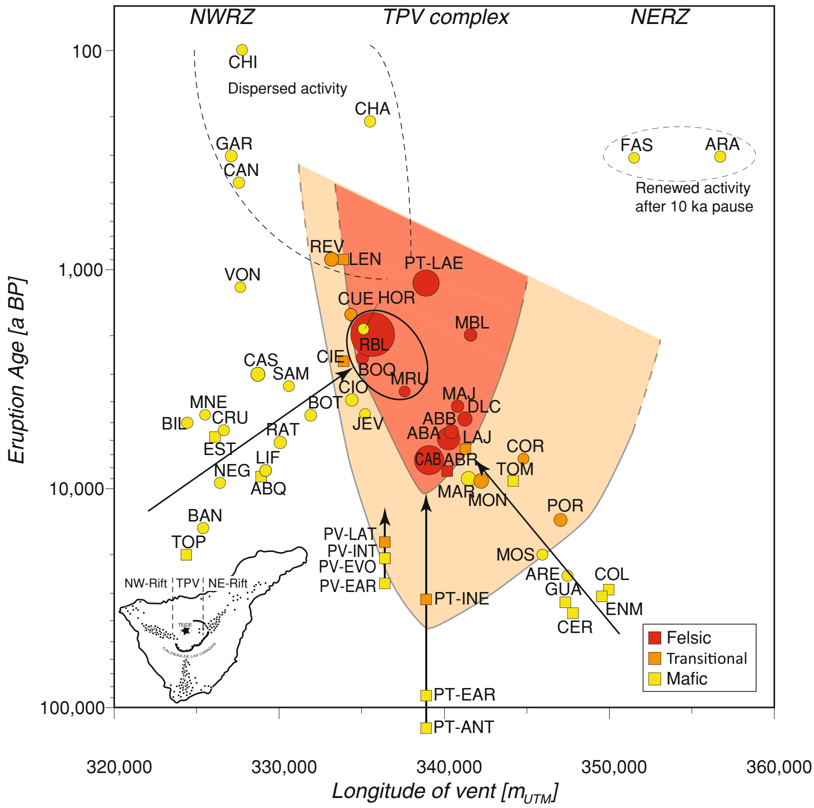

Fig. 9.12 Distribution of vent locations versus eruption age. *Round symbols* denote eruptions for which a volume estimate is available; in these cases, the size of the symbol correlates with the erupted volume. *Square* symbols have no estimate of eruption volume. Note how the activity of central edifice, NERZ and NWRZ migrate towards each other after 30 ka followed by a dispersal of rift zone activity after the central complex erupted significant volumes of felsic material from ~8 to 1 ka. Vent locations of rift zone eruptions prior to 30 ka are not preserved. Eruptions volumes Carracedo et al. (2008), except for Montaña Blanca, which is from Ablay and Martí (2000)

mafic magma to the sides of the central complex due to underplating below Teide's edifice. Since the volume of felsic magma generated by underplating is necessarily limited by the amount of mafic magma present for either fractionation or remelting, both models would imply a waning magmatic system at Teide–Pico Viejo complex. That said, Teide–Pico Viejo is well-monitored and any subsurface activity is certain to be detected weeks to months prior to a potential eruption. This has recently been evidenced in the prelude to the 2011–2012 submarine eruption at El Hierro, where seismic activity increased several months in advance of the eruption, despite the eruption itself being of relatively small volume and magnitude (Carracedo et al. 2012; Troll et al. 2012).

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