Eruptive Styles at the Teide Volcanic Complex

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Abstract

The wide variety of volcanic products composing the Teide Volcanic Complex (TVC) reflects an unusual assemblage of eruptive styles, with a wide range of phenomena represented and only plinian and phreato-plinian styles truly lacking. This diversity is due to spatial and temporal variations in magma composition (mafic magmas of the rift zones and felsic magmas of the central edifice), variable magmatic volatile contents and the interaction of magma with external water (snow, groundwater, etc.). Overall, strombolian eruptions are the most frequent eruptive style at the TVC. Explosive eruptions of felsic material tend to be of low volume, for example, the largest explosive event during the Holocene,

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Montaña Blanca (ca. 2 ka), produced ~0.2 km^3 DRE of phonolitic pumice during an eruptive sequence that reached explosivity of sub-plinian magnitude. Examples of phreatomagmatic activity (surge deposits) have been described both on the northern flanks of Teide volcano as well as from the summit area of Pico Viejo volcano. Until now most studies on volcanic hazard assessment have focussed on ash fall and lava flow hazards in the Canary Islands, but phreatomagmatic eruptions and their potential effects may have to be seriously considered as well.

12.1 Introduction

The definition and classification of volcanic eruptions is a challenging task because of the inherent complexity of the eruptive process and the number of parameters involved (e.g. temperature, silica content, and volatile content of the magma, the presence of external water and the structural state of an edifice). During its evolution, the eruptive activity of a volcano can hence display a variety of styles, some of them very different from previous eruptive stages. These styles may change drastically even in the course of a single eruption, and in the Teide Volcanic Complex (TVC) perhaps the best examples of these changes are derived from the interaction of magma with meteoric water (including snow) and groundwater.

Attempts to classify eruptions using different characteristics (genetic, descriptive, etc.) have resulted in an abundance of terms, many of them redundant and of unclear significance. The simplest classification, however, distinguishes "magmatic" and "phreatomagmatic" eruptions, and depends on the presence or absence of external water (e.g. from the sea, lakes or groundwater) during the eruptive process.

Magmatic eruptions are driven essentially by the magma and its contained gases, and the different eruptive styles which then ensue from variations in magmatic composition and rheology. Following Walker (1973), a widely accepted classification of magmatic eruptions defines types (with progressively increasing explosivity), such as Hawaiian, Strombolian, Vulcanian and Plinian eruption styles. All except the Plinian type are represented in the volcanic succession of the TVC. Hawaiian and Strombolian eruptive styles, commonly grouped as effusive eruptions, are characterised by mafic and intermediate lava compositions, and on Tenerife frequently form multiple vents along fissures parallel to the rift zones (fissure eruptions) (Fig. 12.1). Vulcanian (narrow conduit) and Plinian (wide conduit) eruptive styles are classified as explosive eruptions, and are commonly associated with felsic magma compositions on Tenerife (Wolff and Storey 1983).

Phreatomagmatic eruptions (e.g. Wohletz 1983; Lorenz 1987) occur when large volumes of hot magma mix with water (e.g. groundwater, sea water, lake water and snow and ice melt water). Highly explosive eruptions occur if the magma/water interaction is efficient, i.e. if the balance between fuel and coolant allows for explosive energy release. Transfer of heat (fuel) to water (coolant) becomes more effective as the contact area between hot magma and water increases, for example with initially fragmenting magma. This is because the intensity of phreatomagmatic explosions results from the expansion of heated water and is therefore proportional to the area of water/magma contact during the eruption (Büttner et al. 1999; Morrissey et al. 2000). In this context, highly fragmented magma and an intermediate magma/water mass ratio produce the most explosive eruptions. In general, felsic magmas yield more efficient "fuel–coolant" interactions than mafic magmas, so phreatomagmatic eruptions vary from the lower end of the explosivity range, for example in Surtseyan types (interaction of water with mafic magmas) to the very explosive phreatoplinian types, caused by interaction of water with felsic magmas, which are often an

Fig. 12.1 Panoramic photograph of the Chinyero volcano (Nov. 1909), the latest eruption on the island of Tenerife (Maximilian Löhr, Fotografía Alemana)

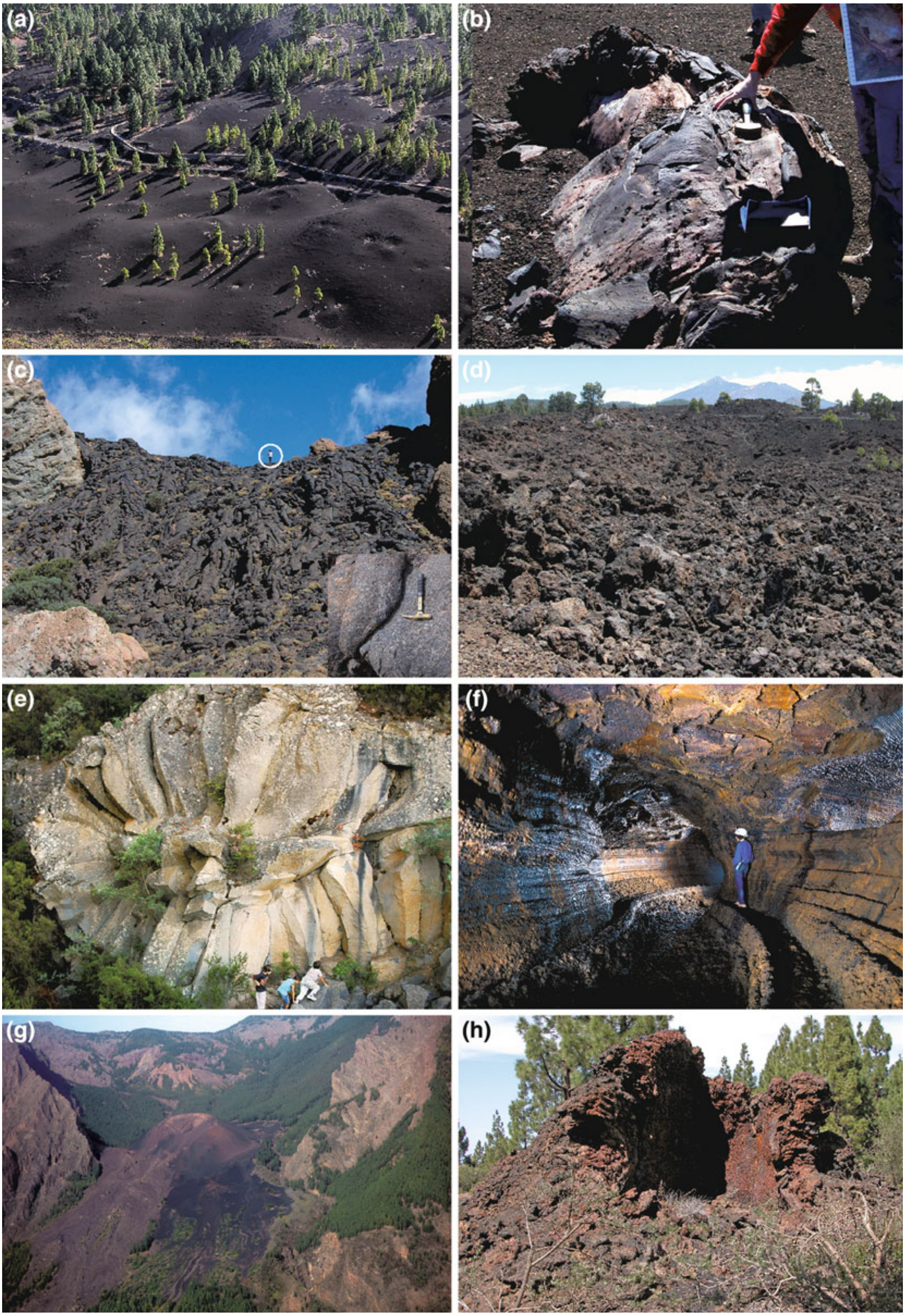
order of magnitude more energetic (Morrissey et al. 2000).

Explosive eruptions are in general relatively scant in the TVC, despite the abundance of felsic volcanism (Araña et al. 1989a; Ablay et al. 1998; Rodríguez-Badiola et al. 2006; and Chaps. 9 and 10). In contrast, highly explosive (Plinian) events are frequent in the older volcanic phases of the Las Cañadas Volcano. The total volume of these older explosive, predominantly phonolitic, eruptions has been estimated at ca. 150 km^3, with single events of about 20 km^3 e.g. Edgar et al. (2007). Martí et al. (2008) defined this difference as follows "*Pre-Teide central activity is mostly characterised by large-volume* (1 –> 20 km^3, *DRE*) *eruptions of phonolitic magmas*, *while Teide–Pico Viejo is dominated by effusive eruptions*". The lower volatile contents (particularly H_2O) and lower viscosity of the peralkaline TVC magmas may account for their lower explosivity (Araña et al. 1989a; Albert-Beltran et al. 1990; Ablay et al. 1995; Rodríguez-Badiola et al. 2006; see also Chaps. 9 and 10). Even mixing of mafic and felsic magmas, a relatively frequent event in the TVC, tends to produce effusive eruptions (Araña et al. 1989b; Rodríguez-Badiola et al. 2006; Wiesmaier et al. 2011; and Chap. 11), with the exception of the Montaña Blanca subplinian event (Ablay et al. 1995). The explosive eruptions that have occurred have mainly been of phreatomagmatic style (Pérez Torrado et al. 2004, 2006; del Potro et al. 2009). From the geological record it thus appears that Strombolian eruptions, producing both mafic and felsic magmas, are the most frequent eruptive style found in the TVC.

12.2 Effusive Eruptions in the TVC

Magmas contain a significant proportion of magmatic gases at high pressure, which are usually liberated to the atmosphere in the initial stages of an eruption. Consequently, eruptions tend to be mildly more explosive at the onset (e.g. Strombolian), fragmenting the lava and producing pyroclasts such as lapilli (Fig. 12.2a), spatters and bombs, some of which reach a considerable size (Fig. 12.2b). After most of the gas has been released, the eruptive style may change to a more effusive one where lava flows are predominant.

In the TVC, the vents of effusive eruptions are largely clustered along the rift zone axes. Therefore, pyroclasts abound at the crest of the rifts, whereas lava flows are more prevalent on the rift flanks. Lava predominantly forms 'a'ā type flows, whereas pāhoehoe morphologies are less abundant, except in the oldest sequences of Teide and Pico Viejo stratocones. There, abundant, smooth to ropy surfaced plagioclase basalt flows occur (Fig. 12.2c). Phonolitic lavas, that in turn frequently form blocky flows, present a wide range of increasingly rough and irregular morphologies (Fig. 12.2d). 'A'ā and blocky lava morphologies are known in the Canary Islands as "*malpaíses*" (badlands).


(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)

◀ **Fig. 12.2** Examples of characteristic features resulting from effusive eruptions in the TVC. **a** Basaltic lapilli fall deposit from the Montaña de Garachico eruption. **b** Basaltic bomb from the area of Montaña Reventada. **c** Pāhoehoe lavas from the initial phase of Pico Viejo. Road near the town of Chío, south Tenerife. **d** Characteristic rough surface ‘a‘ā lava flow from Boca Cangrejo volcano. **e** Internal structure of a channelled basaltic lava flow lobe with radial cooling joints. **f** Interior of the Cueva del Viento lava tube, formed in pāhoehoe lavas during the initial stages of Pico Viejo eruptive activity that flow all the way to the sea. This lava tube is the 5th longest volcanic cavity in the world (after Hawaiian lava tubes). **g** Strombolian cinder cone of Montaña de Arafo (1705 A.D.) **h** Hornito in deposits of the Montaña de Garachico eruption (1706 A.D.)

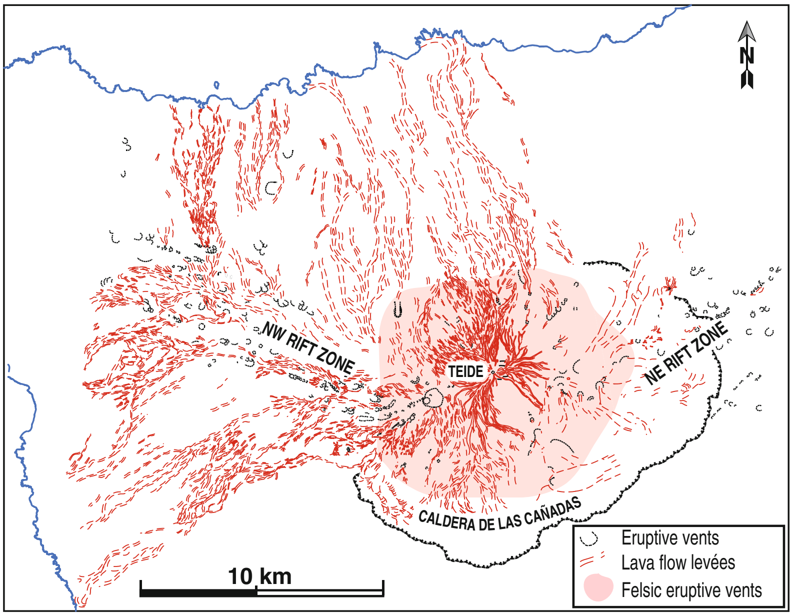


Fig. 12.3 Eruptive vent distribution and flow run-out length in the TVC. Note that a number of felsic as well as mafic flows reach the sea in north and west Tenerife

Associated with effusive eruptions in the TVC are spectacular features like accretionary lava balls (Fig. 12.2e), lava tubes (Fig. 12.2f), cinder cones (Fig. 12.2g), and hornitos (Fig. 12.2h). Detailed morphological descriptions of volcanic cones and lava flows found in the TVC are presented in Chap. 3.

12.2.1 Eruptive Vent Distribution

The distribution of mafic and felsic eruptive centres shows a clear pattern (Fig. 12.3). Mafic eruptions tend to group in the rift zones and form multiple vents from fissures broadly aligned with the main direction of the rift (see Chap. 4). Felsic vents, however, are restricted to the interior of the Las Cañadas Caldera, and often show concentric patterns, forming domes located around the base of the Teide and Pico Viejo stratocones (see also Chaps. 9 and 10). As a result, felsic flows are often thicker than mafic flows on Tenerife but are comparable in total surface area and run-out length, accommodating the larger eruption volumes of the felsic TPV events.

12.2.2 Lava Run-Out Lengths

Mafic and felsic lavas in the TVC differ considerably in thickness, but their total run-out lengths are seemingly similar (Fig. 12.4a). Generally, felsic flow lengths are significantly shorter in other volcanic settings because of their higher viscosity (Fisher and Schmincke 1984; Cas and Wright 1987). Therefore, the total run-out length of felsic (phonolitic) lavas associated with the Teide and Pico Viejo volcanoes

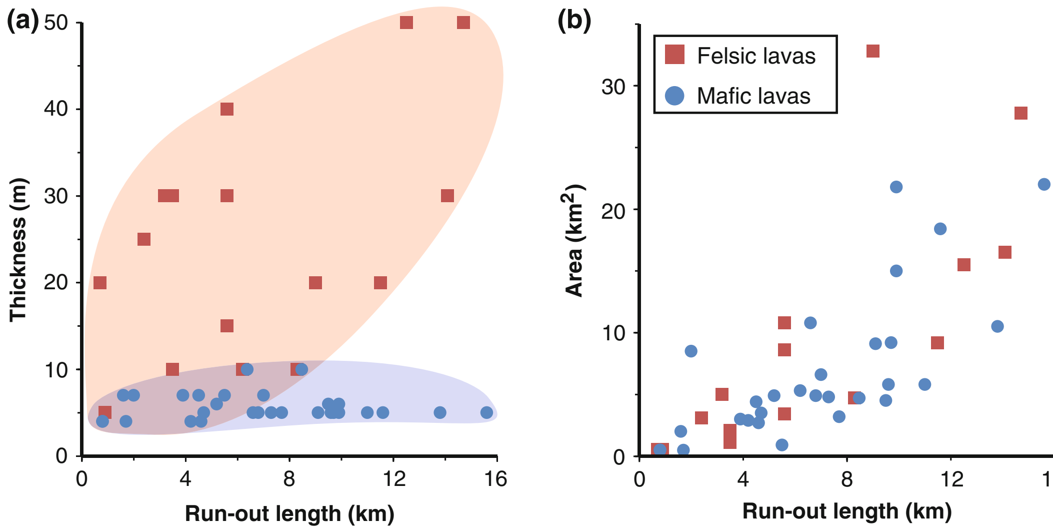


Fig. 12.4 Thickness and covered area vs. total run-out length of mafic and felsic lavas of the TVC. Although the flow thickness of the two compositions differs, flow lengths are similar for both types indicating that composition (i.e. viscosity) is not the sole factor controlling lava flow run-out in the TVC

suggests the influence of parameters other than the rheological properties of the lavas alone. Rodriguez-Gonzalez et al. (2012) analysed the run-out lengths of Holocene mafic flows on Gran Canaria and concluded that eruptive rates, total erupted volume and the topography over which lava flows travel may be as important as lava composition for determining their final run-out lengths. Another aspect affecting the total run-out length of phonolitic lava flows of the TVC is the formation of an external lava carapace (see Fig. 8.21), which generates effective thermal isolation of the lava, and allows flows to travel longer distances producing run-outs approaching those of mafic lavas.

Notably, when run-out lengths are compared with total surface covered by the lava flows, mafic and felsic lava flows frequently show different patterns (Fig. 12.4b). The explanation probably lies in the compositional differences of the two types of lavas. Although felsic lava flows are volumetrically superior (even by some orders of magnitude) to mafic lava flows, they are unable to expand laterally due to their somewhat higher viscosities and thus form pronounced levées that effectively channel the flow downslope (see Fig. 12.5h).

12.3 Magmatic Explosive Eruptions in the TVC

In contrast to the Hawaiian Islands, where eruptions of felsic magmas are scarce to absent, Tenerife and the TVC display a wide variety of these products and associated features (Fig. 12.5), representing probably one of the best examples of felsic volcanism in an oceanic island setting. However, highly explosive eruptive events related to the felsic magmas in the TVC are relatively infrequent and tend to be of low volume. Occasional collapses of asymmetrical domes and phonolitic lava flow fronts cause Vulcanian events, but Plinian eruptions, very common in the older Las Cañadas Volcano, are not preserved in the TVC geological record. So far, the subplinian Montaña Blanca phonolitic event, some 2,000 years ago, appears to have deposited the most explosive eruption sequence within the TVC succession (Ablay et al. 1995).


(a)
(b)
(c)
5 cm
(d)
(e)
(f)
(g)
(h)

◀ **Fig. 12.5** Characteristic felsic products and features of the TVC. **a** Strombolian phonolitic cone of Montaña Majúa. **b** Montaña Blanca-derived airfall pumice in the saddle between Teide and Pico Viejo. The red colour is caused by oxidation of the frothy pumice. **c** Bread-crust phonolitic bomb, Montaña Blanca. **d** Large accretionary lava ball (locally known as Huevos del Teide or Teide's Eggs). This one detached from the front of the Lavas Negras flow (ca. 1240 B.P.), northern slope of Montaña Blanca. **e** Very rough surface typical of phonolitic blocky lava flows, Lavas Negras. Encircled people for scale. **f** Chaotic assemblage of angular blocks of obsidian phonolites from the Montaña Blanca group (El Tabonal Negro). Encircled is a person for scale. **g** An example of a short-length phonolitic flow: Los Gemelos, north of Pico Viejo (image is 600 m across). **h** Pronounced levées in phonolitic flows of Roques Blancos (image is 150 m across). Note that the best growth conditions for the pine trees are found inside the former flow channels, where pumice and rubble accumulate and preserve humidity

12.3.1 The Montaña Blanca Subplinian Event

Montaña Blanca is a large volcanic dome complex formed by phonolitic lavas on the eastern flank of Teide stratocone, nearby the Las Cañadas Caldera region influenced by the NERZ (see Chaps. 7 and 8). The Montaña Blanca eruption can be divided into multiple events, which have been dated at ca. 2 ka (Ablay et al. 1995; Carracedo et al. 2007). A map of this volcanic complex and stratigraphic relationships is provided in (Fig. 8.23). Ablay et al. (1995) also made a detailed study of the different eruptive styles involved in this eruption. The eruption began with lava extrusion, followed by subplinian explosive activity, which produced large volumes of pumice and ash. The eruption ended with lower energy vulcanian and, eventually, dome-building activity. The bulk volume of the pumice and ash deposit from Montaña Blanca is estimated at about 0.815 km^3 ($\approx$0.17–0.25 km^3 DRE), emitted from a NW–SE fissure located at the most elevated area of the Montaña Blanca dome complex. Except at some proximal localities, the pumice deposit consists of a single, well-sorted, massive bed of pale green, crystal-poor, phonolitic, angular pumice lapilli (Fig. 12.6a). The coarseness, good sorting, angularity and grain size characteristics clearly indicate its fallout origin. Isopach and isopleth maps show the deposit to be elongated in SW-NE direction. Ablay et al. (1995) determined a pyroclastic column height of about 15 km, a wind speed of 10 m/s and a minimal area of 40 km^2 covered by pyroclastic fall deposits (see Fig. 14.18). Magma mixing (phonolitic and phonotephritic compositions), a shallow magma chamber and a relatively high percentage of volatiles are the main parameters invoked by Ablay and others to explain the most explosive phase of the Montaña Blanca events.

12.3.2 Gravitational Collapse of Phonolitic Domes and Lava Flow-Driven Explosive Eruptions

Small and disperse outcrops of phonolitic volcaniclastic deposits have been recently reported on the northern slopes of the TVC (del Potro et al. 2009; García et al. 2011). The eastern outcrops on that slope are located close to the western flank of Pico Cabras, in the area of Los Benjamines (del Potro et al. 2009), and the western outcrops close to El Boquerón and Roques Blancos (García et al. 2011). These volcaniclastic deposits are estimated to be of Holocene age by correlation with the general stratigraphy previously defined by the abundant radiometric ages found in Carracedo et al. (2007).

Volcaniclastic deposits of both these areas (the western and eastern outcrops of Teide's northern slope) present similar characteristics: poor lateral continuity, deposit slope angles of 20–30°, variable thickness (<1 to several metres), massive with no bedding or internal flow structures, matrix-supported and a consistently monogenetic (phonolitic) nature of clasts and matrix (Fig. 12.6b). According to del Potro et al. (2009) these features point to a block-and-ash flow deposit derived from gravitational collapses of incandescent asymmetrical domes and/or fronts of lavas flowing over break-in-slope areas.

García et al. (2011) described another type of volcaniclastic deposit found near the Abrunco volcano, which they interpreted as pumice-rich ignimbrites (Fig. 12.6c). Due to the presence of these pyroclastic deposits, the authors argue for potentially higher explosivity in the volcanic history of the TVC than generally assumed: "*The fact that the volume of pyroclastic deposits visible today is small compared to that of lavas does not necessarily imply that explosive activity has been insignificant in the recent evolution of Teide–Pico Viejo. On the contrary, we claim that phonolitic explosive activity has been more significant than previously thought in Teide–Pico Viejo during the Holocene. The evidence we have presented for the syn-depositional erosion of ignimbrites suggests that heavy rainfalls may have occurred in the area during these eruptions, which could explain the rapid disappearance of a significant part of these deposits*".

This type of pyroclastic deposit, however, has not been observed in abundance in the older TVC stratigraphic sequences, either along surficial outcrops or along the *galerías* (water tunnels) crossing the north flank of Teide at different locations and depths (e.g. Carracedo et al. 2007; Márquez et al. 2008; Boulesteix et al. 2012). Moreover, the rapid erosion, suggested by these authors as the rationale to explain the scant volume of these deposits, should have affected the Las Cañadas Volcano succession in the same way, and yet, pyroclastic deposits related to magmatic explosive eruptions are highly abundant there (e.g. Huertas et al. 2002; Edgar et al. 2007).

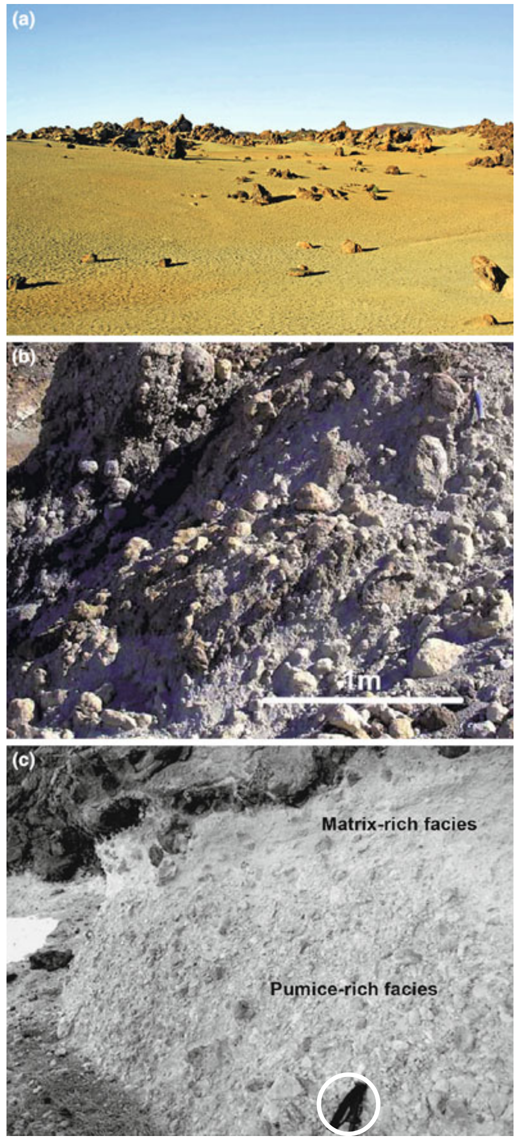


Fig. 12.6 Close-up view of some pyroclastic deposits in the TVC. **a** Pumice pyroclastic fall deposits from Montaña Blanca eruption mantling previous topography. **b** Block-and-ash deposit at Los Benjamines outcrop formed by gravitational collapse of a phonolitic dome (from del Potro et al. 2009). **c** Close-up photograph of El Abrunco ignimbrite showing matrix-rich and pumice-rich facies at Abrunco outcrop. Note the encircled walking stick handle–15 cm for scale) (from Garcia et al. 2011)

12.4 Phreatomagmatic Explosive Eruptions in the TVC

Phreatomagmatic explosive eruptions involving both mafic and felsic magmas, are relatively frequent in the geological evolution of the TVC, but voluminous deposits are scarce. The main outcrops are located at the northern flank of Teide (Calvas del Teide) and encircle the summit of Pico Viejo (Fig. 12.7). There, the water involved in the magma-water interaction must have been derived from snow and ice that accumulate during winter periods.

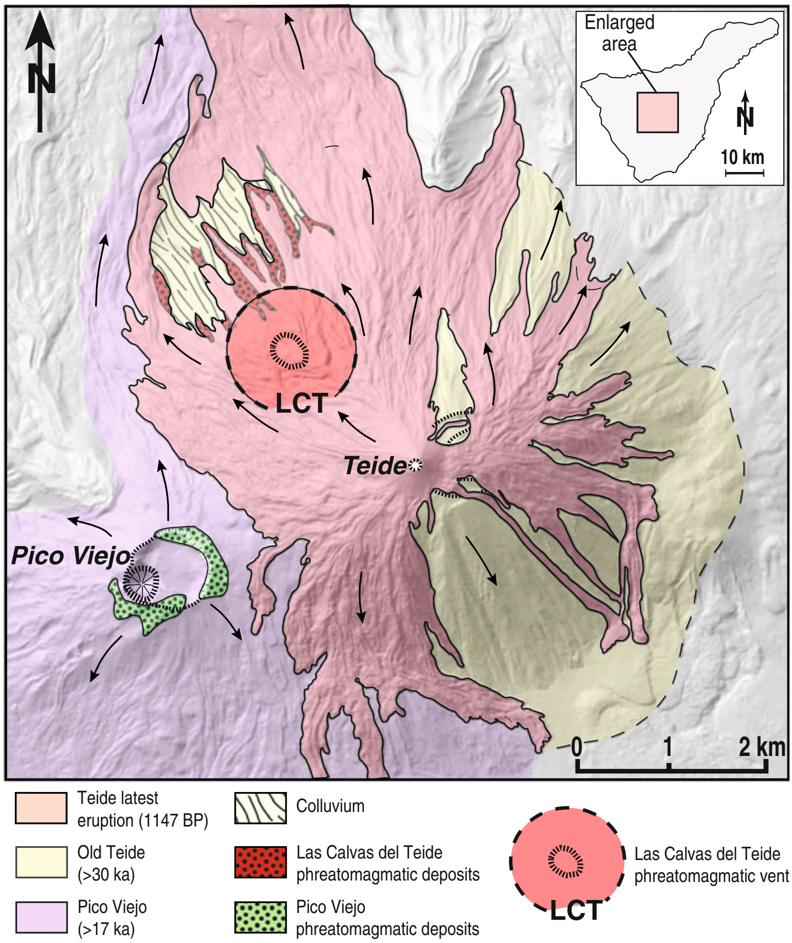


Fig. 12.7 Map showing the extent of phreatomagmatic deposits of Las Calvas del Teide and Pico Viejo

12.4.1 Las Calvas del Teide

This very visible formation was first identified as a phreatomagmatic eruption from Teide during the geological mapping of the TVC carried out between 2003 and 2006 (Pérez Torrado et al. 2004; Carracedo et al. 2007). The deposits appear as thick and off-white, indurated volcaniclastic slabs, devoid of any vegetation (locally known as Teide's bald patches) (Fig. 12.8a and b). Pérez Torrado et al. (2004) described them as being interbedded with thin "Old Teide" phonolitic lava flows (>30 ka), and capped by flows of Pico Viejo volcano (>17 ka). The entire sequence is partially covered by the latest (1150 ± 140 yr BP) phonolitic Teide event (see Fig. 12.8a and b). The scattered outcrops appear along the gullies that cut into the NW flank of the Teide stratocone (Fig. 12.9) and give a sense of the depth of erosion and the subsequent infill of younger lavas. The full stratigraphic column has been resolved by correlation of partial exposures at different localities, which all have slopes that are consistently ~35° (see Fig. 12.9).

The stratigraphic column is composed of six distinct units (Fig. 12.10) (Pérez Torrado et al. 2004, 2006). Thin (<1 m) phonolite flows form the bottom and top (Fig. 12.10a and f) and appear interlayered between the pyroclastic deposits (Fig. 12.10c). Volcaniclastic units show two different lithofacies: laminated, fine grained (Fig. 12.10b and e), and coarse-grained, massive beds (Fig. 12.10d). The laminated deposits appear as alternating layers of coarse (5–10 cm) and fine (1–15 mm) clasts, embedded in an intensely indurated cineritic matrix (Fig. 12.8c and d).

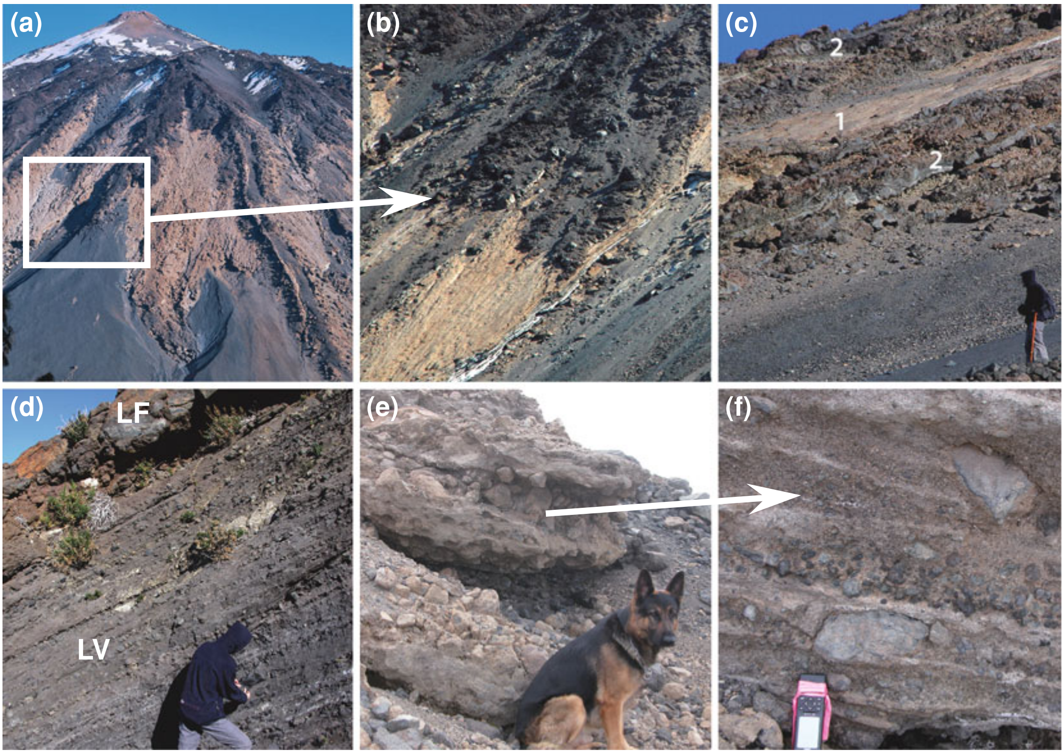


Fig. 12.8 Images of the Las Calvas del Teide phreatomagmatic deposits. **a** General view of the area. Note the indurated and thick white volcaniclastic slabs devoid of any vegetation (Teide's bald patches). **b** Close-up view of the volcaniclastic slabs covered by the Lavas Negras flows. **c** Phreatomagmatic volcaniclastic deposits of Las Calvas del Teide (*1*) alternating with phonolitic lava flows of "Old" Teide (*2*). **d** Close-up view of laminated volcaniclastics deposit (LV) topped by an "Old" Teide phonolitic lava flow (LF). **e** Volcaniclastic deposit outcropping down-slope at Las Calvas del Teide, interpreted as a debris flow deposit. **f** Detail of the debris flow deposit in (**e**)

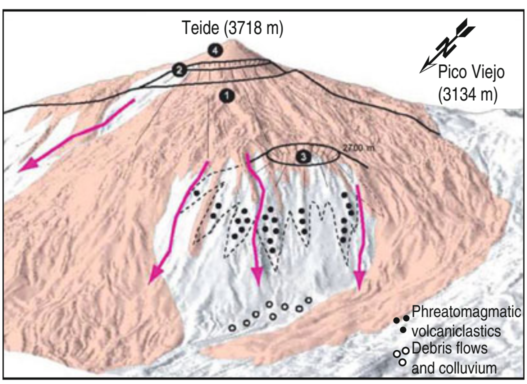


Fig. 12.9 Outcrops of the volcaniclastic and associated deposits from the Las Calvas del Teide phreatomagmatic eruption. *1* Lavas Negras (ca. 1.2 ka). *2* "Old" Teide (>30 ka). *3* Las Calvas del Teide inferred phreatomagmatic vent. *4* Summit cone of the Lavas Negras eruption

Internal depositional features including parallel and low-angle cross-lamination, scour and fills and bomb sags, have been identified in the fine grained layers. Coarse-grained beds show erosive bases, a clast-supported matrix, and a diffuse clast-size distribution with a tendency towards normal grading of the size and number of clasts. Both lithofacies show angular and poorly vesiculated clast types, some of them obsidian.

Of these clasts, del Potro et al. (2009) distinguished two types with similar characteristics to the interbedded lava flows, which they interpreted to be a co-magmatic feature. These clasts are affected by pervasive networks of microfractures, which are typical of magma–water interaction. Del Potro and co-workers suggested that the characteristic induration of the thin laminated matrix-supported units could have been derived from near-syn-depositional alteration of the vitric components by means of a geo-autoclave-type mechanism (Gottardi 1989; Pérez-Torrado et al. 1995). Alteration to zeolite facies would have occurred during the initial cooling of the pyroclastic deposit, implying the involvement of a significant hydrous component during the eruption.

The observed features suggest that these deposits have formed as phreatomagmatic surges. The alternating fine and coarse-grained laminations and the interlayered lava flows point to changing conditions in the magma-water interaction at different eruptive stages, and imply the proximity of the emission vent (c.f. Clarke et al. 2009). The most likely eruptive scenario involves the opening of a lateral vent during a period when the stratocone was covered by a thick cap of snow or ice (Fig. 12.11), a setting first proposed by Pérez Torrado et al. (2004, 2006) and later confirmed by del Potro et al. (2009). Pérez Torrado et al. (2004) interpreted the bulge observed on the mid-northern flank of Teide as being a reflection of the phreatomagmatic vent. An earlier interpretation by Ablay and Martí (2000), however, related the bulge to the scarp of the Icod lateral collapse.

The Calvas del Teide phreatomagmatic deposits change down-slope into debris flow and colluvium deposits (see Fig. 12.9), although the actual transition is covered by later lavas and scree deposits. Therefore, it is currently impossible to determine if a continuous lateral change from pyroclastic to debris flow facies exists. Alternatively, the latter may have formed from erosion of the former (see Fig. 12.8e and f).

Finally, an aspect to analyse is the presence of a N–S trending, sub-vertical dyke intruding the basal flows (Fig. 12.12a) of the stratigraphic sequence. The dyke feeds a thin, scoriaceous flow with abundant olivine phenocrysts (Fig. 12.12b). This mafic intrusion in a highly differentiated stratocone supports the idea that magmas constructing Teide volcano derive from a common deep source that also feeds rift zone volcanism (see Chap. 7). On the other hand, the arrival of mafic magma to the flank of Teide without signs

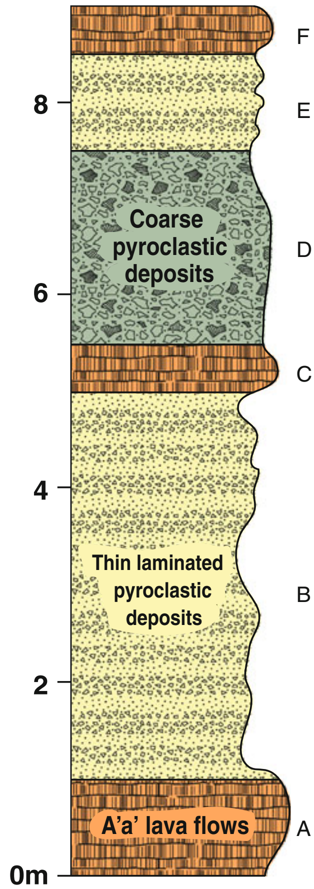


Fig. 12.10 Schematic stratigraphic column of the Las Calvas del Teide area: volcaniclastic deposits (*B*, *D*, *E*) are intercalated with phonolitic lava flows of "Old" Teide (*A*, *C*, *F*) (modified from Pérez-Torrado et al. 2004)

of mixing with felsic magma supports the notion that the current felsic holding chambers beneath Teide are small or largely solidified. This would be consistent with the progressive reduction of phonolitic eruptions of Teide itself over the last 30 ka (Carracedo et al. 2007).

12.4.2 Phreatomagmatism in the Pico Viejo Volcano

Deposits derived from a phreatomagmatic eruption, similar in many aspects to those of the Calvas del Teide, outcrop inside the Pico Viejo crater and mantle the summit slopes of the volcano (Fig. 12.13). The area covered by this Pico

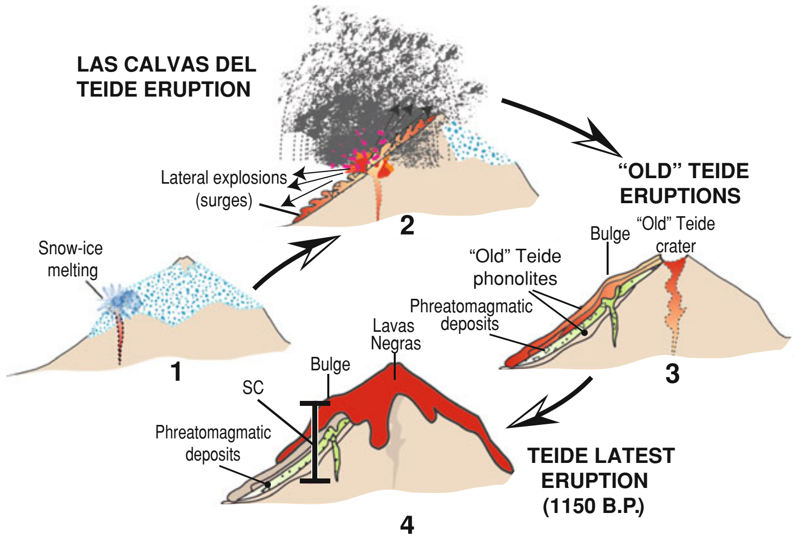


Fig. 12.11 Sketch depicting the probable cause of the Las Calvas del Teide phreatomagmatic event—by the interaction of magma with snow-ice meltwater. SC, stratigraphic column in Fig. 12.10 (modified from Carracedo et al. 2008)

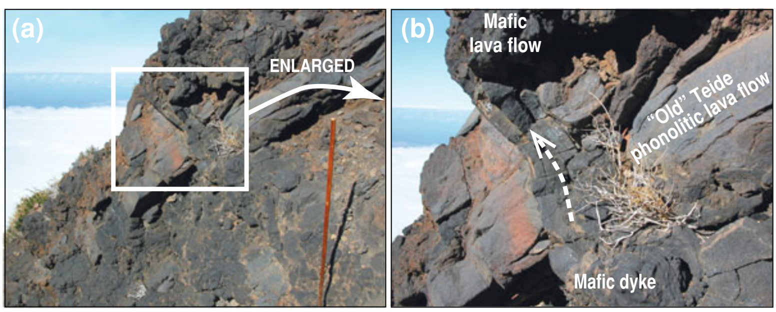


Fig. 12.12 Basaltic dyke cutting a phonolitic flow of "Old" Teide (>30 ka), a relationship that implies the ultimate feeder system to Teide is the same as that of the rift zones

Viejo phreatomagmatic eruption is notably smaller than that of Calvas del Teide (see Fig. 12.7). The relative stratigraphic position of the Pico Viejo deposits indicates a younger age than that of the Calvas del Teide deposits. Ablay and Martí (2000) relate part of this formation to the eruption of Roques Blancos, dated at 1790 ± 60 yr BP (Carracedo et al. 2007).

A detailed study of these deposits was carried out by Ablay and Martí (2000). They describe a 40–80 cm thick layer of weakly indurated, cross-laminated, red-grey surge deposits (Fig. 12.14), dominated by 1–10 mm sized juvenile fragments of plagioclase-basanite scoriae in a heterolithic matrix. Above this lies a scoriaceous plagioclase-basanite spatter and a short-flowing a'a lava originating from the Pico Viejo crater rim (L in Fig. 12.13c). A final layer of unconsolidated explosion breccia (Fig. 12.13d), composed of angular rock fragments up to 1 m across and without juvenile components, can be correlated with the formation of an explosion pit in the SW part of the crater floor (see Fig. 12.13a–c). The onset of this phreatomagmatic eruption may have been caused, as in the Calvas del Teide event, by the interaction of magma with snow and ice

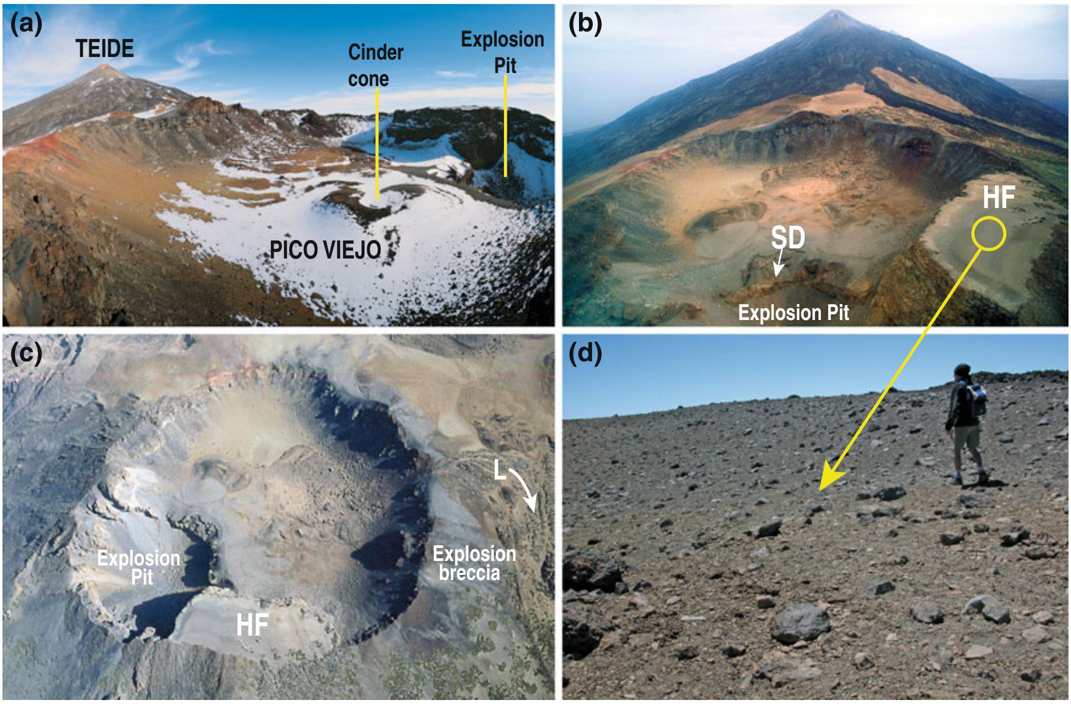


Fig. 12.13 Features of the phreatomagmatic eruption of Pico Viejo. **a** View from the western rim of Pico Viejo crater. **b** Southern part of the Pico Viejo crater wall showing the flat top of the crater-filling sequence. SD: surge deposits. Sub-horizontal flows (*HF*) are covered with explosion breccia deposits from the phreatomagmatic eruption. **c** Aerial view of the Pico Viejo crater showing the extensive explosion breccia deposits (grey colour). A lava flow (L) on the eastern side post-dates the phreatomagmatic event. **d** Close-up view of the explosion breccia deposit mantling the sub-horizontally bedded lava flows that partially fill the Pico Viejo crater (*HF* in **b** and **c**)

Fig. 12.14 Close-up view of pyroclastic surge deposits from the Pico Viejo phreatomagmatic eruption outcropping in the wall of the explosion pit (SD in Fig. 12.13b), which are similar to those mantling the sub-horizontally bedded lava flows (HF Fig. 12.13 **b** and **c**)

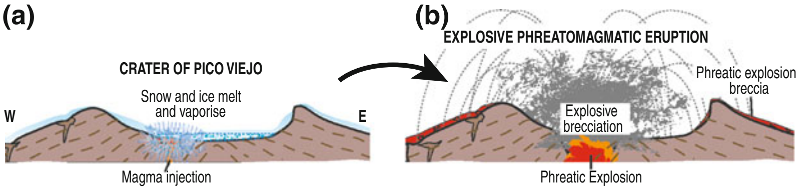


Fig. 12.15 Sketch illustrating the probable cause of the Pico Viejo phreatomagmatic event—by the interaction of magma with snow-ice meltwater. **a** Approaching magma heats the crater floor and melts snow producing considerable amounts of meltwater. **b** Water filters through the highly porous volcanic lapilli and fractured lavas, interacting with the shallow-level magma to cause phreatic explosions (modified from Carracedo et al. 2008)

accumulated inside the Pico Viejo crater (Fig. 12.15). The presence of a permanent aquifer or lake in this area is improbable due to the very high porosity of the volcanic summit deposits.

12.4.3 Phreatomagmatism in the Canary Islands

Besides the outlined examples at Teide and Pico Viejo, examples of phreatomagmatic eruptions exist on all the Canary Islands (Fig. 12.16), with felsic phreatomagmatic events being generally less frequent. Local place names in the archipelago frequently refer to the characteristic white and yellow tones of hydrothermally altered basaltic tuffs (e.g. Caldera Blanca, Lanzarote; Montaña Amarilla, Tenerife), and to wider craters and lower aspect ratio cones of such composition (e.g. Montaña Escachada, flattened mountain, Tenerife). The morphology and size of these phreatomagmatic cones is varied, with numerous examples of tuff-cones, maars, and tuff-rings, particularly on the littoral platforms and outcrops in marine cliffs (Carracedo et al. 2001). The majority of these eruptions are triggered by direct interaction with sea water (e.g. Montaña Amarilla, Tenerife; La Caldereta, La Palma; Montaña Escachada, Tenerife, etc.). In this type of eruption the source of water is unlimited, and the eruption remains phreatomagmatic throughout (e.g. Montaña Amarilla). However, the transition from phreatomagmatic to purely volcanic mechanisms during a single eruption is also observed in some examples [e.g. Montaña Los Erales, (Clarke et al. 2005, 2009)]. The eruption of La Caldereta, a large tuff cone near Santa Cruz on La Palma, is an example of this, as during the final stages, a small Strombolian vent formed with lava flows nested in the centre of the volcano. Another instance is the El Golfo vent on Lanzarote, where magma encountered a finite amount of water at its initial stage of eruption and variable additions of water during subsequent eruptive styles.

Further recorded cases of volcanic activity that have been influenced by magma-water interaction are summarised in Table 12.1. The majority of these phreatomagmatic eruptions are basaltic, but some spectacular felsic events have also occurred in Tenerife [e.g. the phonolitic-trachytic Caldera del Rey twin caldera (De la Nuez et al. 1993)]. Sea water is assumed to be the primary hydrological source, e.g. Caldera Blanca and El Golfo (Lanzarote), Montaña Goteras and La Caldereta (La Palma), La Isleta (Gran Canaria) and Montaña Amarilla and Montaña Escachada (Tenerife). Yet, phreatomagmatic activity is not explained by seawater interaction in all cases, as examples exist far inland as well, such as the Hoyo Negro eruption in La Palma in 1949 (Klügel et al. 1999; White and Schmincke 1999). The Hoyo Negro vent complex on La Palma is located significantly above sea level (at 1,880 m elevation) and extends 400 m along the north–south trending rift that runs along the centre of the southern half of the island. Here, the onset of the 1949 San Juan eruption was characterised by phreatomagmatic activity emanating from a series of vents around the Duraznero crater (Klügel et al. 1999; White and Schmincke 1999). At such altitude, a direct or indirect seawater

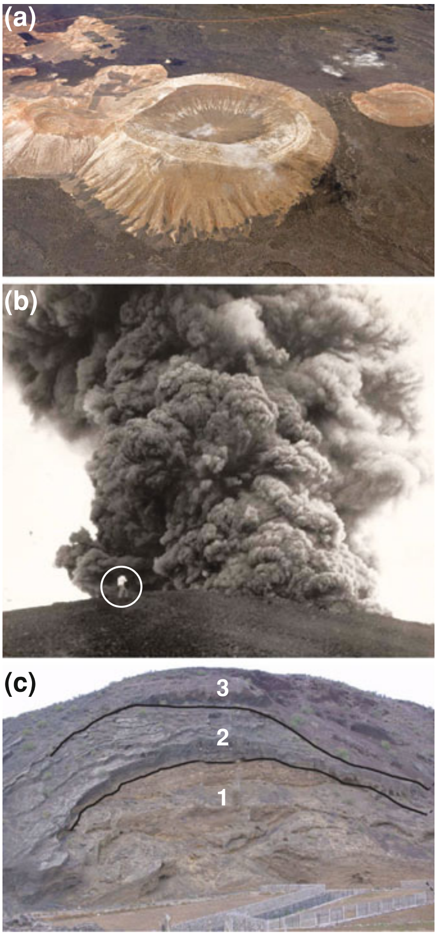


Fig. 12.16 Examples of phreatomagmatic eruptions in the Canary Islands. **a** Caldera Blanca (Lanzarote). Seawater is assumed to be the primary water source for this eruption, which occurred on a shallow coastal platform. **b** The phreatomagmatic eruption of Hoyo Negro (1949, La Palma). The vent is located far inland, at the summit of the Cumbre Vieja rift, thus groundwater or surface water was most probably involved in the eruption. *Note* the height of the phreatomagmatic column can be estimated by comparison to the brave person venturing dangerously close to the eruptive vent. **c** Los Erales, a strombolian vent that began with a hydrovolcanic explosive eruption (*1* in the figure), and ended with an entirely dry solely magmatic strombolian eruptive style (*3*), after a transitional stage during which the water source became progressively exhausted (*2*)

influence appears most unlikely. In this scenario, groundwater or surface water may have been present due to ephemeral pools that formed on the surface of older impermeable ash deposits, hence the name of this area ‘Llanos del Agua’, referring to the presence of water (Carracedo and Day 2002). Other examples of phreatomagmatic activity without seawater interaction are Caldera de los Marteles (Pleistocene) and Caldera de Bandama (Holocene) on the island of Gran Canaria. Caldera de los Marteles, with its crater base located at 1,458 m above sea level, formed within a steep-sided valley (Barranco de Guayadeque), which suggests that phreatomagmatism was induced when rifting along fissures commenced and surface water gained access to the magmatic heat source (Schmincke et al. 1974). On the other hand, Caldera de Bandama, located along a watershed boundary area with its crater base at 217 m above sea level and about 150–200 m depth to the pre-eruption surface, is inferred to have formed by magmatic interaction with shallow groundwater sourced in a detritic layer interbedded in the volcanic substratum (Rodriguez-Gonzalez et al. 2012).

Despite a high abundance of felsic rocks in the TVC, explosive magmatic eruptions are scarce and produce mainly low-volume deposits. One exception is the Montaña Blanca subplinian event, however. Extensive volcaniclastic deposits in the TPV derive from explosive events related to phreatomagmatic eruptions involving both felsic (Las Calvas del Teide) and mafic (Pico Viejo) magmas. Effusive eruptions, mainly of strombolian type, are the most frequent eruptive style observed in the TVC, again with mafic and felsic magmas displaying this mode of eruption.

Araña et al. (2000), in proposing a surveillance network for the island of Tenerife, consider the main volcanic hazards to be lava flows and ash fallout, with little reference to the potential of phreatomagmatic eruptions. A clear record of recent and historic eruptions that display a hydrous influence exists both at Teide and on the other Canary Islands (Table 12.1). The realisation of phreatomagmatism as an uncertain variable in an otherwise low-explosivity eruptive regime (e.g. on the rifts), increases the need for improved understanding of this eruptive style in the Canary Islands and needs to be taken into account for the evaluation of societal vulnerability and risk assessment (see Chap. 14).

Table 12.1 Examples of historic and recent phreatomagmatic eruptions in the Canary Islands

Eruption	Island	Date/age	Duration (days)	Composition	Eruptive style	Proximal to shoreline
Phreatomagmatic eruptions						
Escachada	Tenerife	Pleistocene	n.k.	Basaltic	Phreatomagmatic	Yes
Montaña Amarilla	Tenerife	Pleistocene	n.k.	Basaltic	Phreatomagmatic	Yes
Caldera del Rey	Tenerife	Quaternary	n.k.	Phonolitic/ trachytic	Phreatomagmatic	Yes
Teide (Calvas del Teide)	Tenerife	Pleistocene	n.k.	Phonolitic	Phreatomagmatic	No
Pico Viejo crater	Tenerife	Holocene	n.k.	Basanitic	Phreatomagmatic	No
La Caldereta	La Palma	Pleistocene	n.k.	Basaltic	Phreatomagmatic	Yes
Montaña Goteras	La Palma	Holocene	n.k.	Basaltic	Phreatomagmatic	No
Montaña Amarilla	La Graciosa-Lanzarote	Quaternary	n.k.	Basaltic	Phreatomagmatic	Yes
Caldera Blanca	Lanzarote	Quaternary	n.k.	Basaltic	Phreatomagmatic	Yes
Caldera de Los Marteles	Gran Canaria	Quaternary	n.k.	Basaltic	Phreatomagmatic	No
Caldera de Bandama	Gran Canaria	Holocene	n.k.	Basanitic	Phreatomagmatic	No
La Isleta	Gran Canaria	Quaternary	n.k.	Basaltic/ basanitic	Phreatomagmatic	Yes
Mixed eruptions						
El Golfo	Lanzarote	Quaternary	n.k.	Basaltic	Phreatomagmatic opening phase-Strombolian	Yes
Los Erales	Tenerife	Quaternary	n.k.	Basaltic	Phreatomagmatic opening phase-Strombolian	No
San Juan (Hoyo del Banco, Duraznero, Hoyo Negro)	La Palma	1949	38	Basanitic/ tephritic	Phreatomagmatic opening phase-Strombolian	No
Fuencaliente	La Palma	1677	66	Basanitic	Strombolian with phreatomagmatic phase	No
El Charco	La Palma	1712	56	Basanitic/ tephritic	Strombolian-phreatomagmatic	No
Tinguaton Tao	Lanzarote	1824	90	Basaltic	Strombolian with final phreatomagmatic phase	No

n.k. not known
Sources Klügel et al. (1999); Carracedo et al. (2001), (2007); Carracedo and Day (2002); Clarke et al. (2009); Rodriguez-Gonzalez et al. (2009)

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