Journal of Volcanology and Geothermal Research 181 (2009) 89–105

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

journal homepage: www.elsevier.com/locate/jvolgeores

An analysis of the morphological, geological and structural features of Teide stratovolcano, Tenerife

Rodrigo del Potro [a,b], Harry Pinkerton [a,*], Marcel Hürlimann [c]

[a] Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, UK
[b] Observatorio Vulcanológico y Sismológico de Costa Rica, Universidad Nacional (OVSICORI-UNA), Apdo. 86-3000, Heredia, Costa Rica
[c] Geotechnical Engineering and Geosciences Department, Technical University of Catalonia (UPC), Jordi Girona 1-3 (D2),08034 Barcelona, Spain

ARTICLE INFO

Article history:
Received 1 July 2008
Accepted 14 December 2008
Available online 1 January 2009

Keywords:
Teide
Tenerife
volcanic evolution
volcaniclastic deposits

ABSTRACT

A combined field, GIS and modelling study has given us new insights into the evolution and morphology of Teide stratovolcano in the central part of Tenerife. Central to our analysis was an investigation of the nature and development of a number of enigmatic morphological features, including two large 'bulges' at mid-elevation in the north-western and east–north-eastern flanks. This entailed a detailed analysis of high resolution digital elevation data, coupled with new photogeological, geological and geomorphological surveys which were examined using GIS. Our geological investigations reveal that widespread deposits on the steep northern flanks of the edifice were volcaniclastic deposits. These formed during the collapse of incandescent lava flow fronts and, possibly, domes and lobes. Careful examination of other deposits on the lower north-western flank has shown that they formed during magma–water interactions. Detailed analysis has revealed the presence of small coulée eruption vents, abrupt terminations to lava flows and vertical scarps. We were also able to confirm the presence of two nested gräben, along which there has been extensive hydrothermal alteration. Finite element modelling of the basement beneath Teide and structural stability suggest that the Teide edifice was emplaced on the headwall of the Icod island flank collapse. We conclude that the two bulges are flank vents, similar to Pico Viejo, although on a smaller scale. The presence of these flank vents suggests that conduit blockage has probably been more common than previously estimated on Teide. We suggest that future hazard mitigation measures should take into account the potential for large flank vents forming during future eruptions, the possibility of explosive activity from the central edifice, and pyroclastic density currents in front of advancing flows on the flanks of Teide.

1. Introduction

While our knowledge of the geology of the island of Tenerife has improved markedly over the past decades, geological investigations of Teide volcano are less advanced. Until recently, studies of Teide were carried out as part of investigations of larger areas (Carracedo, 1994, 1999; Martí et al., 1994; Ancochea et al., 1999). More recent mapping, geochemical and petrological investigations on Teide by Ablay and Martí (2000) form the basis of our current understanding of the structure and evolution of the Teide–Pico Viejo complex. The only other geological detailed investigation of part of Teide was by Pérez-Torrado et al. (2004) who studied a small locality on the north-western flank. Although a number of geophysical investigations have been carried out in the Las Cañadas Caldera (e.g. Ablay and Kearey, 2000; Pous et al., 2002), these have not extended to the Teide edifice.

Outstanding problems on the evolution and morphology of the Teide edifice include the significance and mode of formation of enigmatic morphological features on the edifice. These include large 'bulges' at mid-elevation which are apparent on both topographic and slope maps of the edifice. Other features identified on aerial photographs that cannot be interpreted without detailed fieldwork include eruption vents, abrupt terminations to lava flows, vertical scarps, and hydrothermally altered areas. To fully understand the formation of these features, an improved knowledge of the structural stability of the edifice and the volcanological evolution of the volcano are required. To achieve this, we used GIS to analyse data from high resolution aerial photographs and digital elevation models in combination with detailed field investigations and numerical models.

In addition to improving our understanding of the structure and evolution of Teide edifice, the present study aims to provide data on potential hazards on Teide. This was stimulated by a significant increase in seismic activity on Tenerife in 2004 (García et al., 2006; Gottsmann et al., 2006).

* Corresponding author. Tel.: +44 1524593912; fax: +44 1524593985.
E-mail address: h.pinkerton@lancaster.ac.uk (H. Pinkerton).

0377-0273/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jvolgeores.2008.12.013

2. Geological setting

In this section, we present an extensive review of previous work on the geology of Tenerife, the Las Cañadas Edifice and the Teide–Pico Viejo system. The information provided in this section is needed in order to fully understand some of the processes that will be discussed later.

2.1. Tenerife and Las Cañadas

Tenerife, located off the African passive margin in the North Atlantic Ocean, is the world's largest intraplate volcanic island after Hawai'i. The geological evolution of Tenerife spans three main episodes: (a) Miocene fissure-fed, basaltic shield-building eruptions, which continued into a sub-aerial island-building phase. These are exposed as eroded massifs on the north-east, north-west and southern parts of the island (Fúster et al., 1968; Ancochea et al., 1990) (Fig. 1). (b) Plio–Quaternary, post-shield, sub-aerial eruptions which constructed a large, composite, NE–SW elongated central volcanic complex known as the Las Cañadas Edifice. This episode has been sub-divided by Martí et al. (1994) into an older mafic Lower Group (>3.5–2.1 Ma), and a felsic Upper Group (<1.56 Ma) characterised by the cyclic construction of silica-undersaturated, petrologically evolved edifices, that climaxed in large, caldera-forming events. Explosive eruptions from the Las Cañadas Edifice cover most of the southern slopes of Tenerife and sectors of the northern slopes (Bryan et al., 1998; Brown and Branney, 2004). (c) Coeval with the construction of the central edifice, mainly basaltic magmas were erupted along the main structural axes of the island (Ancochea et al., 1990): Dorsal Ridge (NE–SW) and Santiago Ridge (NNW–SSE) (see Fig. 1).

The Las Cañadas Edifice is truncated by a great ellipsoidal depression known as Las Cañadas Caldera. This is thought to have formed by vertical subsidence based on stratigraphic and geochronological data (Araña, 1971; Martí et al., 1994; Bryan et al., 1998), volcanological data (Ridley, 1971; Martí et al., 1996, 1997; Bryan et al., 1998, 2000), and structural and geophysical data (Ortiz et al., 1986; Vieira et al., 1986; Camacho et al., 1991; Aubert and Kieffer, 1998; Ablay and Kearey, 2000; Araña et al., 2000; Pous et al., 2002; Coppo et al., 2006). Martí et al. (1994) and Martí and Gudmundsson (2000) conclude that vertical subsidence occurred at three or more asynchronous, adjacent or overlapping calderas: Ucanca (1.07 Ma), Guajara (0.57 Ma) and Diego Hernández (0.18 Ma). The northern Las Cañadas Caldera wall was removed by the Icod island flank collapse which may have been triggered by the collapse of the Diego Hernández Caldera (Martí et al., 1997; Hürlimann et al., 2000), and it has been further buried by materials from the Teide–Pico Viejo formation (Fig. 1).

2.2. Teide–Pico Viejo

The central part of Tenerife is dominated by Teide–Pico Viejo, a twin, asymmetrical stratovolcano constructed during the last 179 ka. The main edifice, Teide, has a maximum elevation of 3718 m a.s.l.

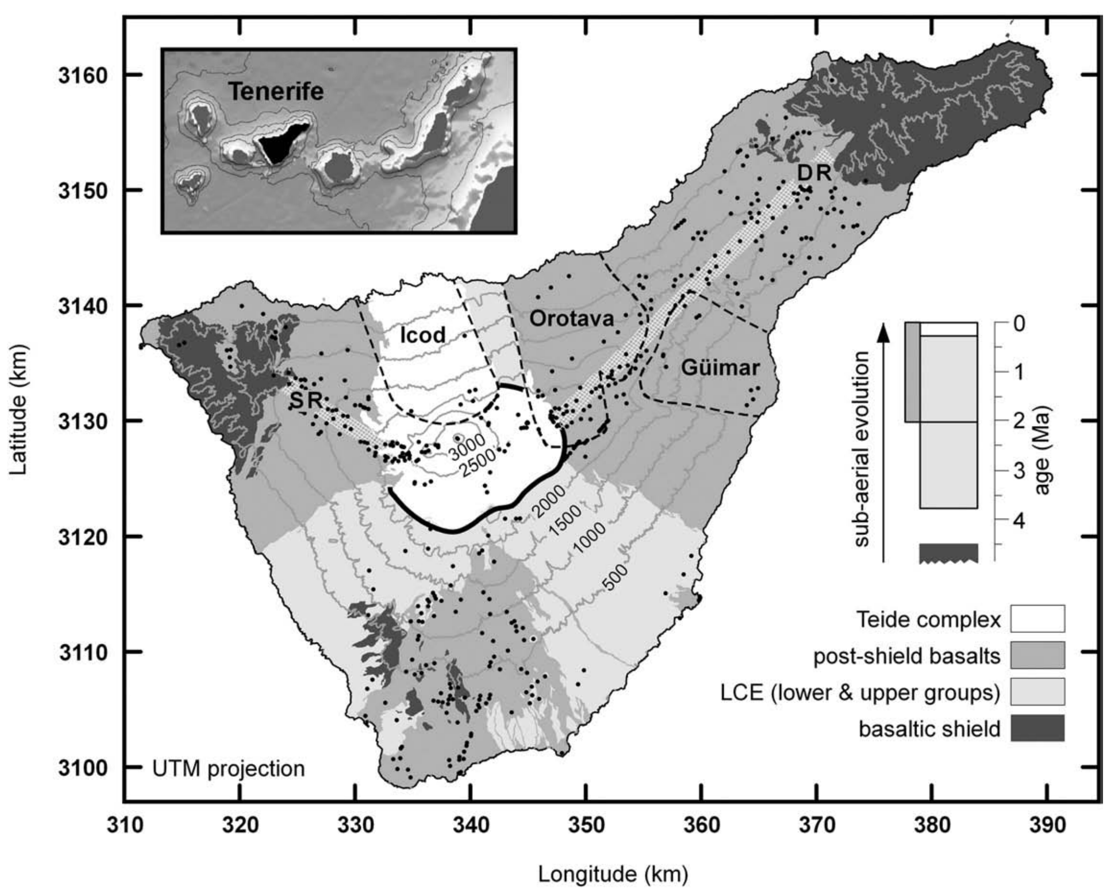

Fig. 1. Simplified geological map of Tenerife. The key on the right shows the chronology of the sub-aerial evolution of the island. The Las Cañadas Caldera wall is represented by a thick black line, crosshatched areas show the Santiago Ridge (SR) and the Dorsal Ridge (DR). The discontinuous lines show the extent of the three major island flank collapse events and the black dots indicate eruption centres. The position of the headwall of the Icod landslide is introduced following Ablay and Hürlimann (2000). Inset shows the location of Tenerife within the Canary Island archipelago and the African continental margin to the right.

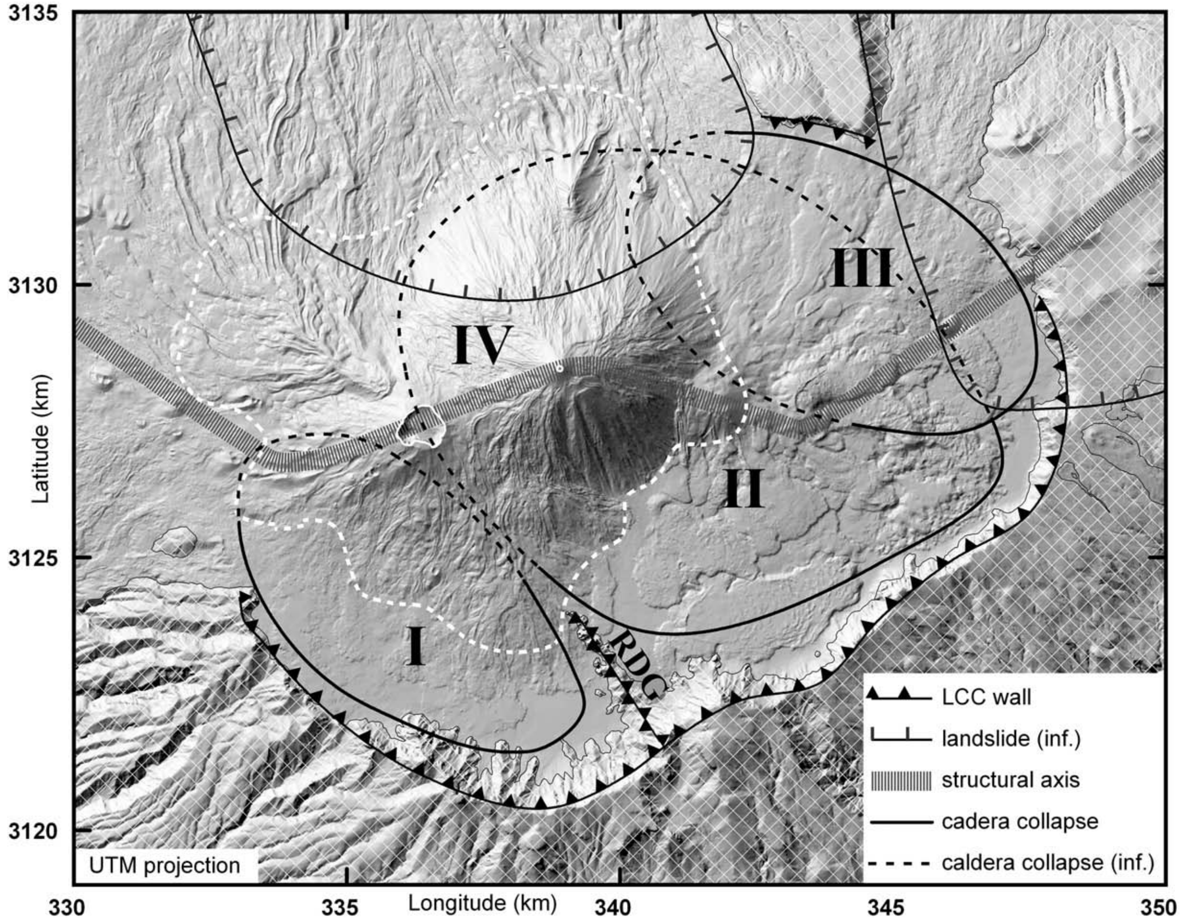

Fig. 2. Shaded relief map of the central area of Tenerife illustrating the morphology and evolution of the Upper Las Cañadas Edifice Group and the observed and inferred extents of the adjacent collapse calderas and island flank collapse landslides (after Martí and Gudmundsson, 2000). Crosshatched areas indicate pre-Teide–Pico Viejo materials. The discontinuous white line denotes the base of the Teide and Pico Viejo stratovolcanoes and other satellite vents, and the continuous white lines indicate the rims of the summit craters. RDG denotes the position of the Roques de García spur and roman numerals chronologically indicate the location of main activity during the four cycles of the Upper Las Cañadas Edifice Group – I: Ucanca, II: Guajara, III Diego Hernández, and IV: Teide–Pico Viejo.

2.2.1. Tectonic setting: implications for the emplacement of the stratocones

Episodes of vertical and lateral collapses have largely modified the stress-field during different stages of the evolution of the Las Cañadas Edifice (Martí and Gudmundsson, 2000). The last activity of the Lower Group and the entire Upper Group followed a linear north-easterly evolutionary pattern along the Dorsal Ridge. However, after the last major modification of the Las Cañadas Caldera (~179 ka ago), the Teide–Pico Viejo formation developed within the depression west of the Diego Hernández Caldera (Fig. 2). Ablay and Martí (2000) noted that the formation of the Icod depression by landsliding would affect the local stress field and may have focussed extensional stresses at the Icod headwall, as is inferred to have taken place on the old basaltic massifs in Tenerife (Walter and Schmincke, 2002; Walter et al., 2005) and on Stromboli (Tibaldi, 2004). This could have resulted in northerly migration of the main structural axis of the island, and may have influenced the location of Teide edifice and been responsible for the “W-shaped” intra-caldera stress field (Ablay and Martí, 2000). Teide's main satellite vents, Pico Viejo (3100 m a.s.l.) and Montaña Blanca (2740 m a.s.l.), are positioned to the east-southeast and west-southwest of Teide, following the structural axis.

The location of the unexposed Icod landslide headwall is unknown. Some authors place it as far as the Las Cañadas Caldera wall (Carracedo, 1994; Huertas et al., 1994; Watts and Masson, 1995; Ancochea et al., 1998; Cantagrel et al., 1999), whereas geophysical, geometrical and slope stability analyses (Ablay and Hürlimann, 2000; López, 2002; Pous et al., 2002; Coppo et al., 2006) suggest that it is located beneath the Teide–Pico Viejo edifice. Thus, depending on which of these models is correct, Teide may either be an edifice nested in a landslide embayment, or the main edifice of the fourth intra-caldera cycle, located at the headwall of the Icod landslide and the floor of Las Cañadas Caldera. In both models, the basement is likely to have played a key role in controlling and constraining the evolution and morphology of Teide.

2.2.2. Lithology of the Teide edifice

Rocks exposed on the surface of the Teide–Pico Viejo complex are mainly mafic to intermediate, with an increasing volume of felsic material during more recent eruptions (Ridley, 1970, 1971; Ablay and

Table 1
Nomenclature, composition and location of the exposed units on Teide's flanks (modified from Ablay and Martí, 2000)

Member	Sub-member	Composition	Exposure
T-L		Phonolite	All flanks – mainly northern
T-K		Phonolite	Upper Icod valley
T-J	T-J2	Phonolite / trachy-phonolite	Summit, southern and south western flanks
	T-J1	Phono-tephrite / tephri-phonlite	Summit, southern and south western flanks
T-I		Tephri-phonolite	Eastern and southern flanks
T-H		Tephri-phonolite	Upper Icod valley ?

Martí, 2000). Borehole investigations down to 1750 m a.s.l. beneath the Las Cañadas Caldera floor (which do not reach pre-Teide–Pico Viejo materials) show that the erupted magmas have evolved from the oldest basanitic lavas through to the more recent plagioclase basanite, phono-tephrite and tephri-phonolite lavas (Ablay and Martí, 2000). The oldest member exposed on the flanks of Teide (member T-I following the nomenclature proposed by Ablay and Martí, 2000, Table 1) is comprised of tephri-phonolite lavas, which outcrop on the eastern and southern sectors of the Teide edifice (Fig. 3). The upper surfaces of the lava flows are scoured and denuded and the lavas on the southern flank are cut by deep drainage gullies. Older tephri-phonolites (member T-H) may outcrop in the upper sectors of the Icod valley (Ablay and Martí, 2000). More recent phono-tephrite/tephri-phonolite (member T-J1) and phonolite/trachy-phonolite (member T-J2) lava members outcrop on the summit and southern flank regions. T-J1 lavas are also cut by drainage gullies on the southern flank.

There is considerable uncertainty over the stratigraphic position of the unit on the Teide and Pico Viejo northern overlap. This unit has previously been attributed to Pico Viejo, but evidence from elevation data and our mapping and morphological analysis suggest that at least part of this was erupted from Teide and could be T-I or T-J. The most recent melanocratic, glassy, porphyritic phonolite lava flows (member T-L) overlie all other members (Ablay and Martí, 2000). ^{14}C dating on lava flows 13 km away could provide a minimum age limit

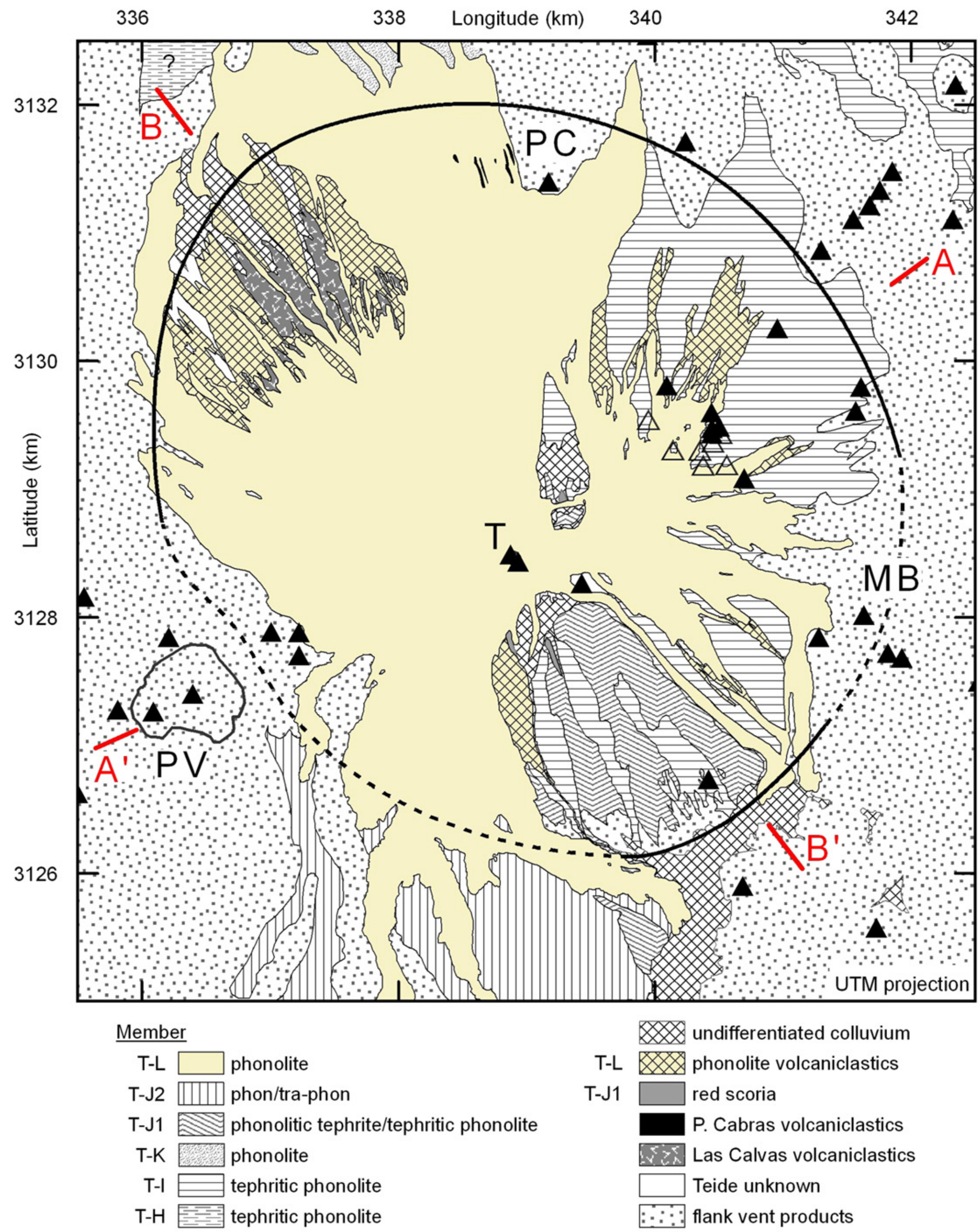

Fig. 3. Detailed geological map of the Teide edifice based on Ablay and Martí (2000). Note the small uncharacterised patches to the west–north-west of the summit region near the Teide and Pico Viejo overlap. The thick black line and discontinuous black line respectively indicate the observed and inferred base of the Teide edifice. Filled triangles indicate eruption vents and open triangles inferred eruption vents. The main vents of the Teide–Pico Viejo formation are shown: Teide (T), Pico Viejo (PV), Montaña Blanca (MB), Pico Cabras (PC). The nomenclature and composition of the Teide units is taken after Ablay and Martí (2000) – see Table 1. A–A′ and B–B′ indicate the location of the cross sections in Fig. 5 and Fig. 15.

for pre-T-L lavas of ~17.6 ka (Carracedo et al., 2003). However, if that age corresponded to T-I, the overlying T-J1 and T-J2 members could be considerably younger. Carracedo et al. (2003) dated the overlying T-L lavas at 1240 BP although Quidelleur et al. (2001) suggest they are ~600 years younger. Glacial and periglacial landforms on Teide observed by Ablay and Martí (2000) suggest a similar upper age limit for T-I.

Pérez-Torrado et al. (2004) examined a series of deposits on the north-western flank and interpreted them as old phreatomagmatic deposits from a flank edifice which they name Volcán de las Calvas del Teide.

3. Methods

The present study uses a combination of detailed field observations, photogeological interpretation, geochemical and petrographical analyses, and numerical modelling to improve our knowledge of the evolution and structure of the Teide–Pico Viejo stratovolcano.

A range of large-scale geomorphological features on Teide were identified using colour aerial photographs (1:18,000 scale) in conjunction with a digital elevation model with a 10 m mesh derived from 1:5000 cartography produced by GRAFCAN. Slope morphology (aspect and angle) and shaded relief maps were computed using a Geographical Information System (ArcGIS – ESRI, 2005). Enlarged aerial photographs (1:5000) and oblique photographs, together with measurements and observations in the field, were used to identify smaller scale geomorphological features and to locate volcanic vents on the Teide stratocone. The geological map published by Ablay and Martí (2000) was used as a base map for geological interpretations, although we used a smaller scale for detailed mapping of key localities, and this has led to significant modifications of the original map. To complement the mapping, we examined thin sections of rocks from important exposures which have not been described by other workers. In addition, 419 joint orientation measurements from the summit and north-western flank regions have been recorded to study structural patterns.

The influence of regional tectonic setting and of the pre-Teide basement structure on its emplacement, morphology and potential edifice instabilities have been assessed using numerical models following methodologies applied to Stromboli (Apuani et al., 2005), Vesuvius (Russo et al., 1997), Mt. St. Helens (Voight et al., 1983; Paul and Gratier, 1987), and Orizaba (Concha-Dimas, 2004) amongst others. All our models were developed using the commercial 2-D finite element software PLAXIS 8.2 (PLAXIS bv, 2006).

4. Enigmatic features on Teide – a description

The following sections contain a description of key morphological and structural features encountered on the Teide–Pico Viejo complex. The interpretation of these data and their structural implications will be presented in Sections 5 and 6.

4.1. Large-scale features

4.1.1. The base of Teide

Teide has a complex basal break in slope, caused by the juxtaposition of the three main edifices and a number of smaller flank vents (Fig. 4). The western slopes of Teide merge into the Pico Viejo

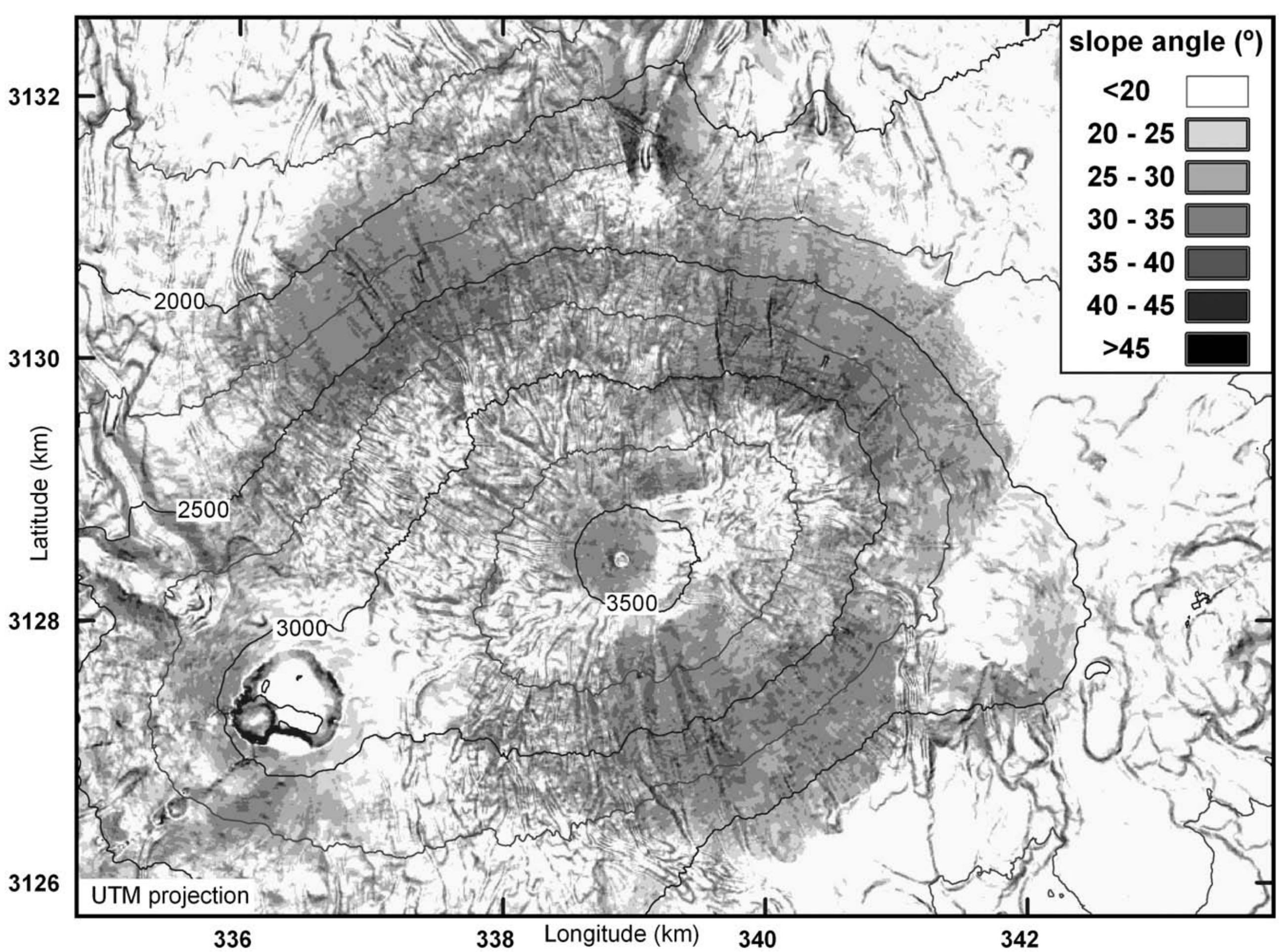

Fig. 4. Slope angle map of Teide edifice.

edifice, leaving a re-entrant between the edifices to the north and forming a gentle saddle at 3050 m a.s.l. The south-western re-entrant is obscured by a bulge at 2700 m a.s.l., which Ablay and Martí (2000) argue is the continuation of the Roques de García spur. Along the southern and southeastern sides, the base of the edifice is concealed by the current Las Cañadas Caldera floor at 2250–2350 m a.s.l., whereas the break in slope to the north and northeast is moderated by the gentler transition from the Teide cone to materials infilling the northward-sloping Icod landslide embayment, at approximately 1800–2000 m a.s.l.

4.1.2. Bulges on Teide

The overall shape of Teide displays a marked convex-up geometry due to the presence of two outstanding bulges at mid-height on the east–north-eastern and north-western flanks (Fig. 4). Teide has steep lower flanks, with the steepest slopes (~35°) directly beneath the bulges and a much flatter, broad summit region with slopes ~15°. The east–north-eastern bulge (Fig. 5) is located at a prominent change in gradient which runs for a total horizontal distance of 1250 m following the 3125 m contour. The oldest member to outcrop on the edifice (pre-17.6 ka T-I) is present both above and below this bulge. An even more prominent break in slope is encountered on the north-western bulge (Fig. 5) which lies at 2700–2750 m a.s.l. on the north-western flank, The break in slope plunges westerly 2° and runs for a total horizontal distance of 1500 m. The formation of the bulge preceded the emplacement of T-L member. Neither bulge appears to have been laterally truncated. Instead, each diminishes gradually towards both ends, leaving constant ~30° slopes: along the eastern central axis towards Montaña Blanca, along the section encompassing Teide summit and Pico Cabras flank vent, and into the Teide–Pico Viejo overlap to the west.

4.2. Small-scale features

4.2.1. More localised changes in slope

Analysis of aerial photographs has revealed shorter, localised breaks of slope around the summit area, where black phonolitic flows either abut remnants of old structures or have ponded and split, possibly marking the location of a change in paleo-slope (Fig. 6). In the field, the sides of lava flows in these locations characteristically display prominent 10–15 cm wide fractures that are infilled by clastic lithic material, and in some locations the flow fronts have become completely detached and have moved 2–4 m downslope. The Teide summit cone has a very complex northern basal slope break where phonolitic scree deposits form pools and ridges.

4.2.2. Scarps in the summit area

Morphological analysis of the summit region of Teide reveals three steep inward dipping scarps, noted by Ablay and Martí (2000). Two of these form prominent curvilinear features on the southern flank at elevations of 3480 and 3550 m a.s.l., and only the outer feature is visible at an elevation of 3450 m a.s.l. on the northern flank (Fig. 6). Eastward-directed T–L lava flows can be traced to inside the inner scarp to the south and to the break in slope to the north, inside the outer-northern scarp (Fig. 6). This break in slope is thought to mark the position of the buried inner-northern scarp. A vesicular, red scoria unit from T–J1, containing elongated bombs and small bomb fragments (~20 cm), outcrops south of the outer-southern scarp and, alongside T–J1, is the youngest unit to be cut by the outer scarps. However, T–J1 material is also present inside the outer-scarps. More recent hydrothermally-altered T–J2 lavas within the outer scarps are cut by the inner scarps.

4.2.3. Domes and coulées

Along, directly below, and directly above the east–north-eastern bulge are a series of dome/coulée structures feeding T-I lava flows (Fig. 6). These features are on average 5–6 m above the surrounding ground. They are 10–20 m wide and display conspicuous radial columnar jointing (Fig. 7). Directly beneath the southernmost vent (Fig. 6), lava flows fed by the coulée-forming eruption flowed horizontally for 10–15 m following the paleo-topography, before plunging parallel to the current slope of the cone, thus giving a clear indication of the break in paleo-slope. The same unit of tephri-phonolites erupted from these vents (T-I) can be followed above the vents to underneath T-L lavas. The T-I lavas are also seen in a number of locations close to the summit region, where they appear to be cut by the outer-northern summit scarp. Field and aerial photographic mapping show evidence of twelve eruptive vents in this region (Fig. 6).

4.2.4. Spatter ridges

A ~50 m long spatter ridge oriented N129°E has been identified in the region between the two northern summit scarps, directly east of

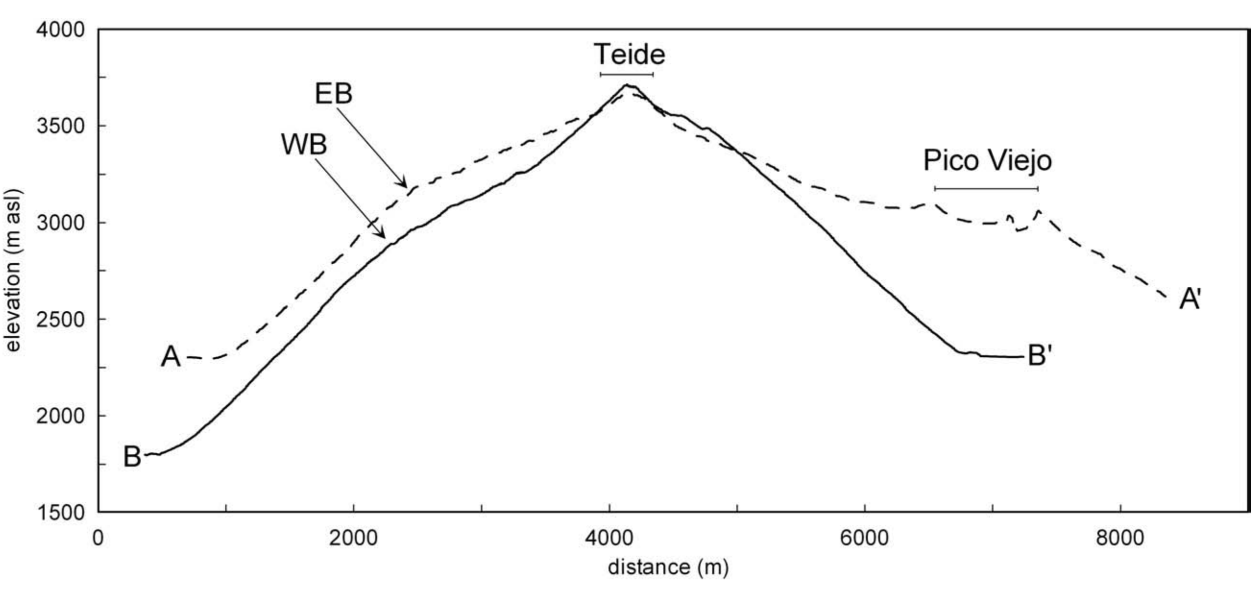

Fig. 5. Cross-sections of Teide edifice with a 1.5 vertical exaggeration. See Fig. 3 for the location of the cross-sections. Note the two prominent bulge-denoting slope breaks: on the east–north-eastern flank at an elevation of 3100 m (EB) and on the north-western flank at an elevation of 2700 m (WB).

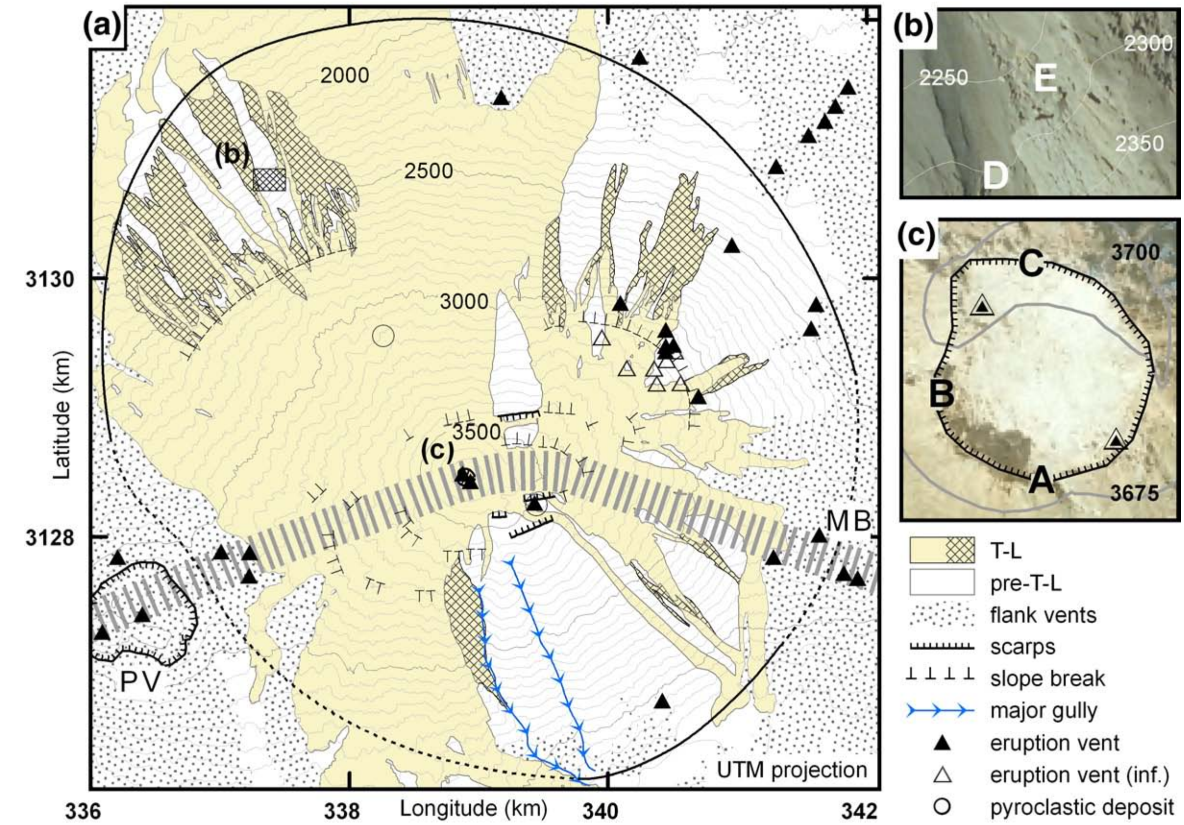

Fig. 6. Simplified map of Teide edifice indicating local morphology and location of minor deposits and precipitates. The continuous and discontinuous black lines represent the observed and inferred base of Teide respectively. The thick discontinuous line illustrates the location of the inferred structural axis (see Fig. 2). A, B, C, D and E in (a) and (b) indicate the location of the stereoplots shown in Fig. 9.

the cable-car house (Fig. 8). The ridge is inferred to have formed on top of a fissure that erupted vesicular, magic magma from T-J. A similar ~125 m long, 4–5 m wide, structure has also been identified on the T-L member phonolites, aligned N127°W along the western flank of the summit cone (Fig. 8). This dyke-like feature displays prominent sub-radial columnar jointing. The columns have distinct 4–6 cm wide dark, chilled margins that encase hydrothermally-altered clay-rich material. The unaltered material is vesicular and grades into welded spatter towards the western end of the ridge.

4.3. Joints

Joint orientation measurements have been used in the past to study macro-structural patterns, edifice evolution and regional stress

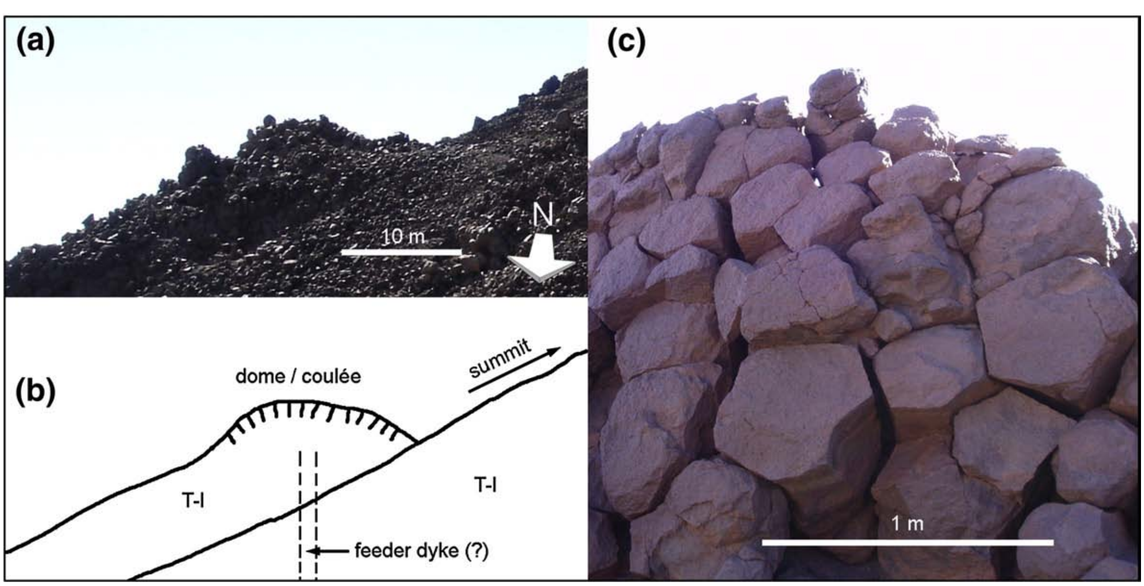

Fig. 7. (a) Photograph and (b) field sketch of a dome/coulée on the eastern bulge, looking south. (c) Close up view of the sub-horizontal prominent columns observed on the domes.

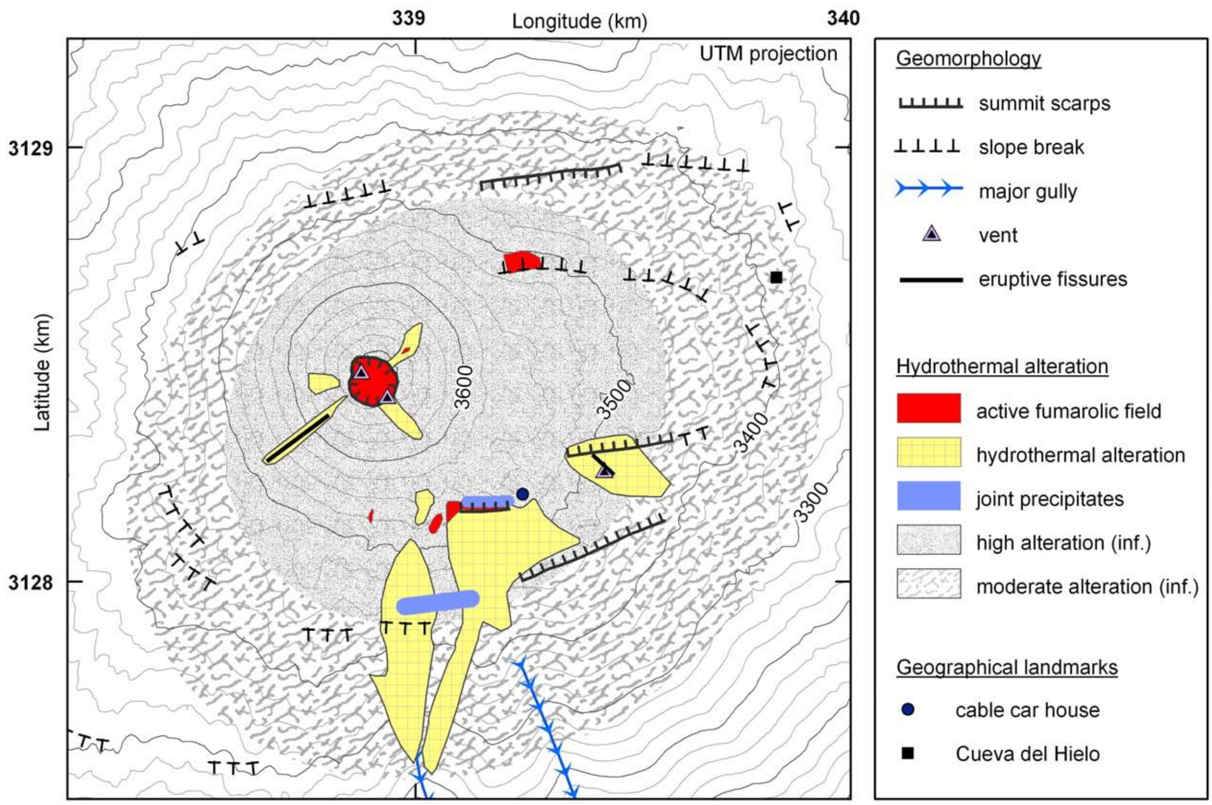

Fig. 8. Detailed morphological and hydrothermal alteration features on the summit region of Teide.

fields in volcanic edifices: e.g. Orizaba (Zimbelman et al., 2004) and Stromboli (Tibaldi et al., 2003). We measured a total of 419 joints on two different areas of Teide: around the summit area and on the north-western flank (Fig. 6). We have not been able to identify large-scale fractures, so all measurements were made on fractures with lengths <5 m. Stereoplots of locations A, B, and C (Fig. 9) show three well defined families of joints: two sub-vertical and one sub-horizontal, crossing at ~90° to each other. Locations D and E present one family of sub-vertical joints and one family of vertical joints perpendicular to each other. Our data suggest that all joints formed either during emplacement or cooling of lava flows. A similar situation was described by Moon et al. (2005) for lava flows on White Island Volcano.

It therefore appears that, in spite of the significant number of macro-structural features present on the edifice, at an outcrop scale there are no systematic, structurally controlled patterns of joint orientations.

4.4. Hydrothermal alteration

Hydrothermal alteration in the summit region of Teide is mainly concealed within the outer scarps and is mostly pervasive to selective but also occurs as local surface precipitates and fracture fillings. Here alteration is visible in three fumarole fields and numerous outcrops (Fig. 8). The highest degrees of alteration are found inside the summit crater where XRD analyses suggest that acid-sulphate argillic alteration has transformed phonolites into alunite and alunite–kaolinite-rich soils (del Potro and Hürlimann, in press). Outside the region delimited by the outer summit scarps, pervasive hydrothermal alteration of heavily fractured lavas can be observed inside the upper region of major gully erosion. In the narrow region between 3420 and 3470 m a.s.l. these lavas are cemented by joint-infilling precipitates (Fig. 8) which our petrographic analysis suggests is mainly crystalline kaolinite. Similar joint-infilling precipitates are present on the T-J2 hydrothermally altered lavas exposed along the inner-southern summit scarp.

4.5. Volcaniclastic deposits

4.5.1. Pyroclastic deposit

The hydrothermally altered, previously uncharacterised outcrops to the east of the cable-car house close to the position of an inferred eruptive fissure (Fig. 8) include minor pyroclastic deposits (Fig. 6), that mantle the eastern section. Volumetrically, most of the exposed material is colluvium, ranging from coarse sand to 40 cm blocks, with most of the material in the 2–10 cm range, although water-saturated soil 5–10 cm below the surface suggests the presence of a high proportion of clay. The pyroclastic deposit comprises elongate, vesicular pumice clasts 3–6 cm across, and sub-angular lithics of lava up to 7 cm in diameter. The well-cemented matrix consists of sub-angular gravel and clay, with rare monolithic plutonic xenoliths. A similar, smaller pumice deposit was observed beneath the T-L phonolites north of the summit region (Fig. 6).

4.5.2. T-L volcaniclastics

The emplacement of member T-L phonolite lava flows was clearly volume-limited, as described by Guest et al. (1987) and Pinkerton (1987) for Etna. Most have drained channels, high levées and clearly defined lobate flow fronts (Fig. 3). However, where these flows reached the break in slope at the east–north-eastern bulge and north-western bulge the flows terminate abruptly at the slope break. Only one of the phonolitic flows that flowed over the north-western bulge maintained its structure. Directly beneath the bulges, the slopes are formed of scree deposits of mainly grey-bluish co-magmatic phonolitic blocks, which can be traced back to the abruptly terminated phonolitic flow fronts. At one location, beneath the north-western bulge, a black phonolitic ´a´a flow appears from beneath the scree slope and flows to the northeast.

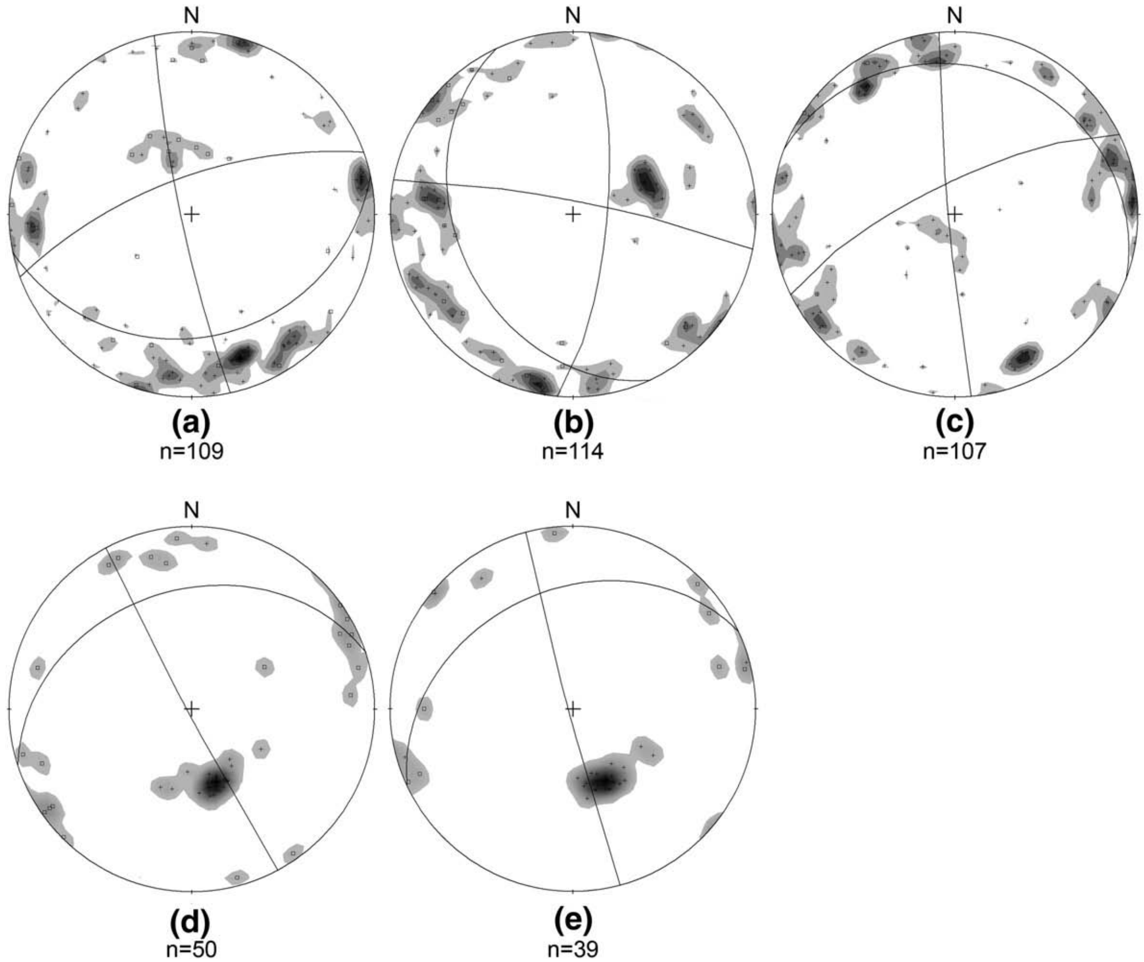

Fig. 9. Stereoplots of joint plane orientation pole concentration contours of the summit crater and north-western flank of Teide. See Fig. 6 for location. All plots are lower hemisphere with 1% area contours. n indicates number of measurements. Thick black lines indicate most significant joint directions at each location, interpreted in all cases as cooling fractures.

4.5.3. Las Calvas volcaniclastics

The steep region beneath the north-western bulge exposes a complex succession of volcaniclastic deposits capped by the T–L member (Figs. 10 and 11) (Pérez-Torrado et al., 2004). Stratigraphic relationships with older Teide products cannot be established. This deposit, which outcrops extensively on the north-western side of Teide, is of major significance for the evolution of the volcano and consequently will be described in detail. The area studied contains two significantly different facies divided by a 15 m-deep, 50 m-wide embayment, on a 35° slope (Fig. 11a).

The eastern wall exposes a 10 m-thick sequence of thick, blocky, and thin fine beds with interbedded thin lava flows, welded deposits, large (4–5 m diameter) phonolitic accretionary lava balls and breccias (Fig. 11c). The base of the exposed succession is a loose, fresh, dark deposit of fine ash. Individual blocky beds are between 0.5 and 2 m thick and are massive, non-cemented and clast-supported and they contain

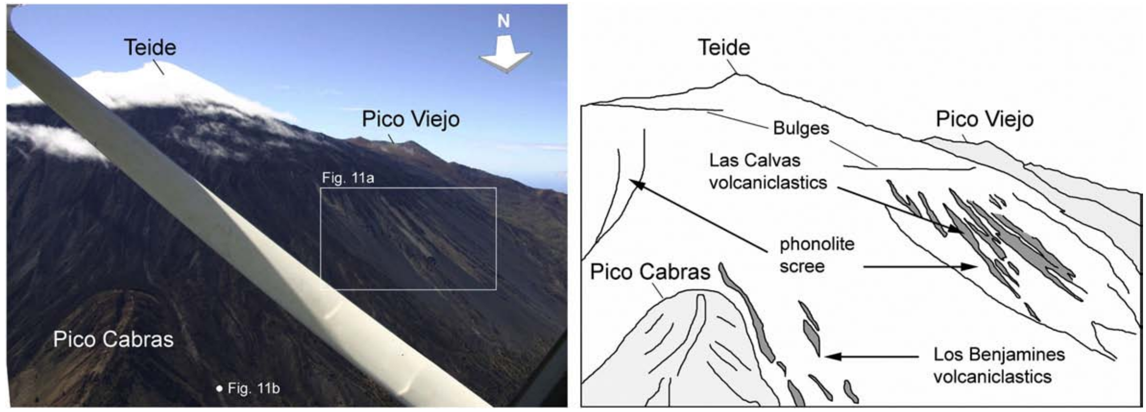

Fig. 10. Oblique aerial photograph of the northern flank of Teide looking SSW. The sketch illustrates the location and extent of the main features observed on this flank of Teide.

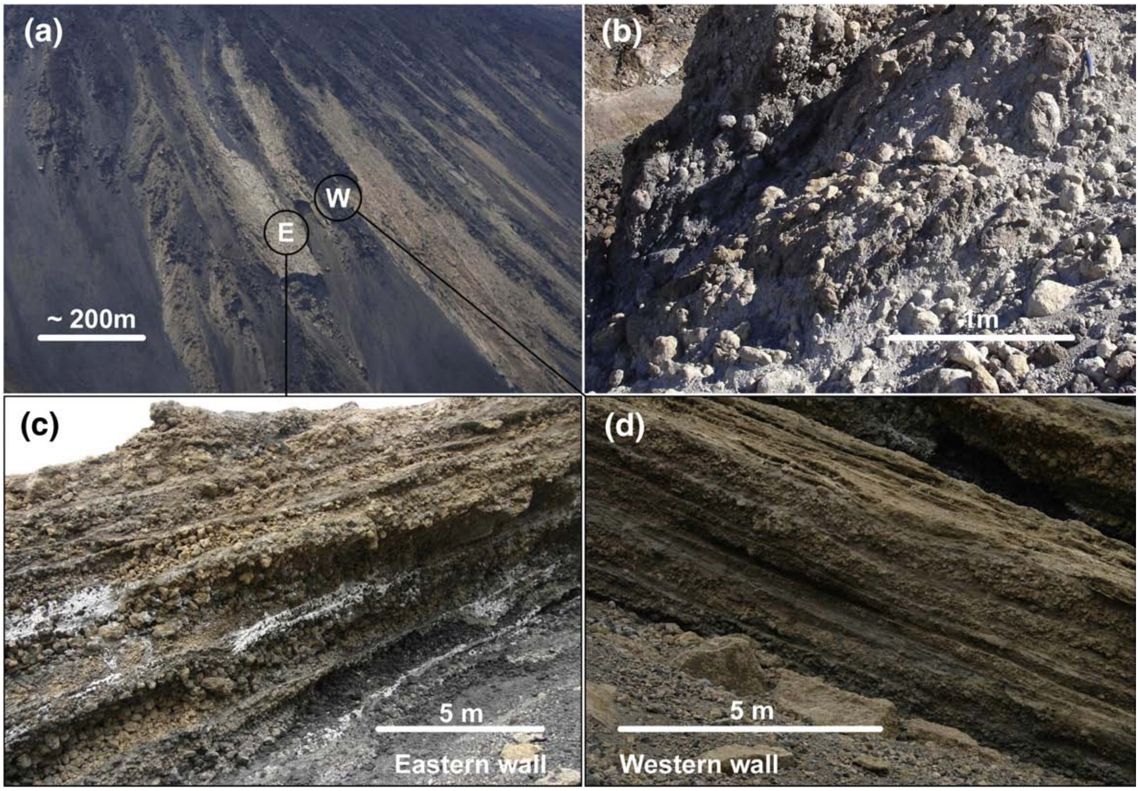

Fig. 11. Photographs of volcaniclastic deposits. (a) Oblique aerial photograph of the Las Calvas volcaniclastic deposits illustrating the location of the outcrops studied. Note the collapsed flow fronts of the overlying phonolite flows and the phonolitic scree deposits beneath them. (b) Close up view of the Los Benjamines volcaniclastics. (c) and (d) show close-up view of the eastern and western walls respectively of the Las Calvas volcaniclastic deposit studied.

angular to very angular lithics 10–30 cm across, with varying small proportions of fines. Internal bedding structures show bimodal clast-size distribution with a tendency for inverse grading, and less than 20% of the blocky units contain flow structures – mainly cross-stratification. Most blocky layers are capped by 10–15 cm-thick coarse sand-size, well-cemented, matrix supported, volcaniclastic units, which are mostly massive with a slight tendency towards normal grading. Erosion horizons are found where loose blocks have been incorporated into the overlying well-cemented fine unit, whereas the same block units show sharp planar bottom contacts without erosive features.

Petrographic analysis indicates that both the thick, blocky and thin, fine units comprise two distinctive magma types: a main alkali feldspathoid-phyric, slightly vesicular lava with clinopyroxenes and a small proportion of large iron–titanium-oxides, and a second lava unit containing fewer and smaller feldspar phenocrysts with a significantly higher proportion of plagioclase. In the matrix-supported samples, these two magmas are affected by pervasive, extensive networks of micro-fractures which suggest magma–water interactions. Alongside these two magma types, the thin, fine units also contain a volumetrically subordinate, red glass-bearing clinopyroxenes (15%) and a few needles of alkali-feldspars (5%) that grade into the main, previously described magma.

Interbedded lava flows of varying composition, which flowed down similar paleo-surfaces, have distinct characteristics. Mafic to intermediate flows display well-defined flow nuclei enclosed by well-developed autoclastic breccia, whereas evolved phonolitic lava flows have no defined structure and instead appear as thick, matrix-free, block-supported, scree deposits (similar to Section 4.5.2), which contain large (4–5 m) accretionary lava balls. Volumetrically minor welded volcaniclastic layers contain a fine-grained matrix supporting large (30 cm), sub-rounded, mostly non-vesicular, polylithic lava clasts with no lineation or visible flow structures. No pumice was observed in any of these units.

A 2.5 m-thick succession of thin (5–50 cm) volcaniclastic beds exposed on the western wall (Fig. 11d) dips 35° to the northwest, overlying the units on the eastern wall. Most beds are clast-free and supported by a fine-grained matrix, but some beds are matrix-free and contain cobble-size clasts. The finer-grained units are cemented, whereas the clast-supported units are loose and poorly consolidated. Many units are massive, although one sand-size, matrix-supported unit shows a slight alignment of 6 cm long, slightly elongate pumice clasts, and several thin layers of silt-size material show marked flow structures: pinching out, and splitting and coalescing of units and alignment of elongated clasts. No erosional contacts are observed within these beds and vesicular clasts are found only in two units. These units on the western wall resembled those described by Pérez-Torrado et al. (2004) somewhere in this area. The exact position of the outcrops they describe is not given, but we assume it is west of this locality.

4.5.4. *Los Benjamines volcaniclastics*

T-L lava flows west of Pico Cabras are underlain by a homogeneous volcaniclastic deposit with a minimum thickness of 4 m. The deposit outcrops on a 20° slope forming N–S oriented, ~200 m-long, 10 m-wide ridges abutted by T-L flows (Fig. 10). The deposit can be traced between adjacent ridges and is estimated to cover a minimum area of 0.1 km^2. In common with the Las Calvas volcaniclastics, this unit yields significant information, which is important for the evolution of Teide and hence will be described in detail. It is a pale-coloured, massive, matrix-supported unit, that comprises a fine-sand-silt-size, well-cemented matrix and rounded, 5–30 cm, fresh, dark, feldspathoid-phyric, clasts (Fig. 11b). No bedding or flow structures are observed. Petrographic analyses reveal the monogenetic nature of the deposit, with both clasts and matrix containing two distinctive magma types: a dominant alkali feldspar-phyric unit containing plagioclase feldspars and clinopyroxenes in a glassy groundmass, and a volumetrically subordinate finer grained unit with fewer and smaller alkali feldspars in a pale brown glassy groundmass. A rim of colourless glass is observed along the contact of both magma members, but only on the clasts. This suggests a magma mixing origin, in agreement with the petrological findings of Ablay et al. (1998).

The base of the unit cannot be seen, although it appears to overlie Pico Cabras products. The minimum age of the deposit is constrained to be 0.6–1.2 ka by the overlying T-L lavas. Thus cross-cutting relationships and morphological observations suggest that the volcaniclastic ridges were generated prior to the emplacement of T-L lava flows, which were confined to the narrower inter-ridge channels of erosional origin.

5. Enigmatic features on Teide – origin and significance

In this section we assess the significance and origin of the features described in Section 4. Smaller scale features and deposits are analysed first because they are important for the discussion on the formation of the bulges in Section 6.

5.1. Domes/coulées on the east–north-eastern bulge

The conspicuous radial columnar jointing within the coulée/dome structures on the east–north-eastern bulge (Fig. 6), together with the large size and degree of development of the columns (Fig. 7) suggests that they developed in contact with cooler surrounding media. It is unlikely that small quantities of ground water would have generated the observed columns. The location of these structures on a 30° slope precludes a permanent body of standing water; instead it is suggested that they were erupted into ice or snow, possibly during the last glaciation. This would provide a maximum age limit in accordance with previous estimates. However, these structures are heavily eroded, making it difficult to determine their original size and the depth at which they formed.

5.2. Formation of nested summit gräben

Our morphological and geological findings provide additional support for a model described by Ablay and Martí (2000) that interprets two pairs of inward facing, steep, vertical scarps on the summit region of Teide as the sum of at least two nested summit collapses. The outer collapse has an elliptical E–W (3×0.9 km) geometry. Its extent beyond the prominent scarps can be traced along a semi-continuous break in slope underneath the T-L lavas (Figs. 6 and 8). Its eastern margin is concealed between the T-J "Cueva del Hielo" lava tube and the T-I lavas observed beneath T-L lavas on the eastern flank (Figs. 3 and 8). Along the southern margin, the continuation of the collapse structure across the top section of the erosional gullies is indicated by the presence of joint infilling precipitates. The absence of mantling pyroclastic products and the cross-cutting relationship of T-J1 products, both cut by and inside the northern scarp, suggest that this structure formed during the T-J1 eruption. Ablay and Martí (2000) suggest it occurred as a consequence of tumescence during the initial stages of the T-J1 eruption.

The more recent inner collapse has a similar, elliptical (1.3×0.4 km) geometry. Its margins can also be traced along slope breaks on the overlying material. However, the highly irregular slope breaks at the foot of the northern flank of the summit cone are attributed to the annual accumulation of snow and ice. The inner collapse's elongated geometry, parallel to the outer collapse, suggests that it is a minor, nested gräben. Crosscutting relationships with the T-J2 pumice deposit mantling the T-J1 inlier between the northern scarps (Ablay and Martí, 2000), the pyroclastic deposit with plutonic xenoliths in the uncharacterised patch east of the cable-car house, and further pumice deposits on the upper-northern flanks (Fig. 6) suggest a component of explosive activity and summit pit-crater collapse, possibly during the final phase of the T-J2 eruption. The inferred extent of the summit collapses is given in Fig. 12.

The presence of small active fumarole fields and areas of hydrothermal alteration along the inferred rims of the gräben suggest that

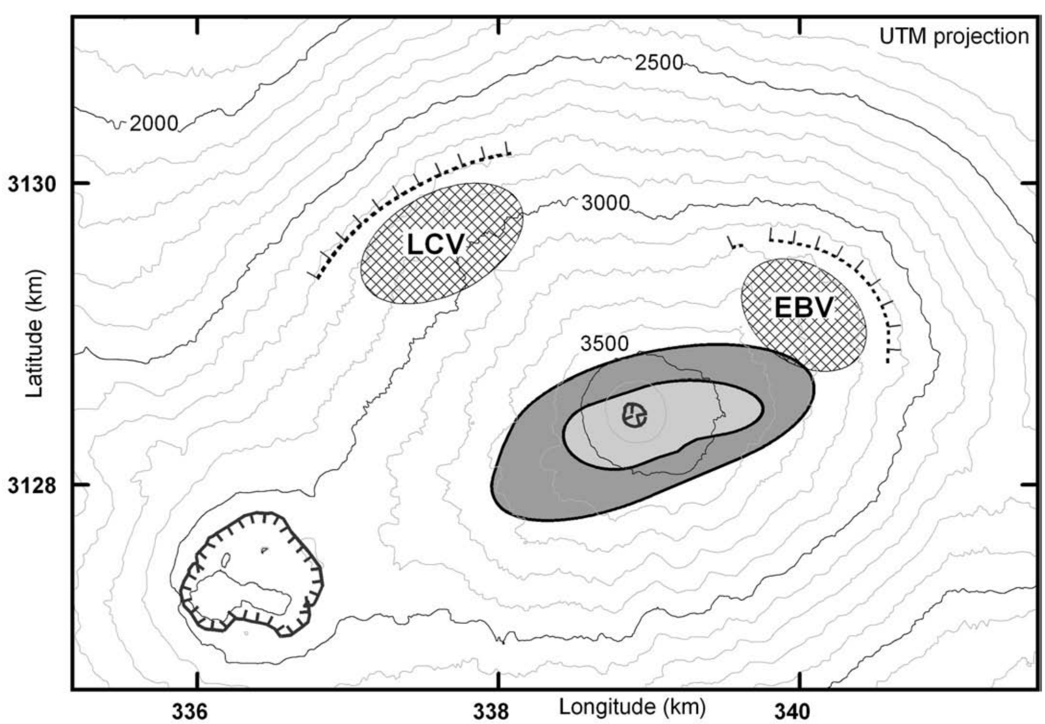

Fig. 12. Topographic map of the T-PV edifice illustrating the extent and location of the two inferred Teide summit collapses (light and dark shadings). Crosshatched regions show the inferred position of the flank vents which generate the bulges – LCV: Las Calvas Volcano, and EBV: East–north-eastern bulge vent. Note that the size of the inferred summit collapse of the flank vents is similar to that of Pico Viejo.

these vertical structures are major pathways for hydrothermal fluids. The presence of these vertical fractures could indicate that hydrothermal alteration might be broader than previously anticipated, and this might have serious implications for the stability of the edifice, as has been suggested for other volcanoes (López and Williams, 1993; van Wyk de Vries et al., 2000; Reid et al., 2001; Cecchi et al., 2005).

5.3. Origin of the volcaniclastic deposits

5.3.1. Phonolitic T-L deposits

Phonolitic T-L deposits exposed beneath the bulges are interpreted as a succession of small lava flow-fed hot rock falls and rock avalanches, similar to those seen on Santiaguito (Rose et al., 1976) and Arenal (Alvarado and Soto, 2002). Increased strain rate at the oversteepening slope break coupled with the high viscosity of phonolitic lava resulted in the collapse of active lava flow fronts. In at least one location on the north-western bulge, incandescent phonolitic scree appears to have re-accreted at the foot of the edifice and continued to flow as an 'a'a lava flow (Fig. 3).

5.3.2. Las Calvas volcaniclastics

The repetitive succession of thick, block-supported and thin, fine, matrix-supported facies that form the Las Calvas volcaniclastics suggest cyclicity during the formation of this unit. The extensive micro-fracture patterns in the thin, fine unit suggest magma–water interactions and contrasts with the unfractured block samples, despite both having the same composition. The presence of red glass on the fine, matrix-supported samples is interpreted as a consequence of the rapid cooling of this unit. The entrapment of small blocks, from the block-supported unit, within the overlying thin, fine, matrix-supported facies suggests that both were formed by a single block and ash flow event. The pre-formation scenario must have involved a recent structure comprising solid material (currently forming the blocky facies), and partially molten magma which was thermally shocked in contact with water (currently forming the indurated fine, matrix-supported facies). We suggest that this structure could have been a growing dome which experienced many lobe collapse events.

The characteristic induration of the fine grained matrix-supported units could derive from post-depositional alteration of the vitric components. The alteration shows no lateral or vertical gradation and does not change in intensity with distance from the emission centre. Following the work by Pérez-Torrado et al. (1995) on the non-welded, lithic-rich ignimbrites of the Roque Nublo formation in the neighbouring island of Gran Canaria, a syn-emplacement 'geoautoclave' alteration mechanism is proposed. This process has been summarised by Gottardi (1989) and implies a significant phreatomagmatic component during the eruption, which agrees with the extensive micro-fracture systems observed in thin sections. The unit-forming block and ash flows must have been too dense and too poorly expanded to permit the water vapour to be separated from the vitric fragments during transport, causing syn-emplacement alteration between the two components whilst they were still hot. However, the total volume of entrapped water vapour cannot have been volumetrically large or the material would not have been deposited on a 35° slope. Such a closed-system alteration mechanism explains why the dark ash deposit at the base of the sequence remains unaltered and loose.

The origin of the large volume of water needed to generate a large number of phreatomagmatic eruptions remains unresolved. It can be argued that the domes grew within a high-level, water-filled vertical collapse embayment. However, such a scenario appears to be unlikely because the main aquifer is currently 700 m beneath Las Cañadas Caldera floor (Soler et al., 2004), more than 2000 m beneath the summit. The absence of large volumes of water on Teide edifice is supported by the low mean annual precipitation on Teide (368 mm), high permeability in the unsaturated zone (2–10 m/day) (Farrujia et al., 2004) and no evidence of high-level perched aquifers. Following a recent model developed for Etna (Behncke et al., 2008), significant amounts of water could have been present in moist hydrothermally altered rocks, causing rootless hydromagmatic events by interacting with volcanic density currents flowing over them. Alternatively it could be argued that the domes were erupted into ice.

5.3.3. Los Benjamines volcaniclastics

In a similar way to the phonilite T-L deposits, the Los Benjamines volcaniclastics are interpreted to be the deposits of lava flow-fed block-and-ash flows, although they could also result from dome-lobe collapses. The roundness of the clasts is attributed to the material being hot during emplacement. Compositionally the deposit could be T-J and its lithification could either be by diagenesis or syn-emplacement 'geoautoclave', analogous to the Las Calvas volcaniclastics.

6. Formation of the bulges

Different hypotheses for the origin of two bulges at mid-elevation are proposed. In addition to the data presented in Section 4, the analysis of these large-scale features involved the development of

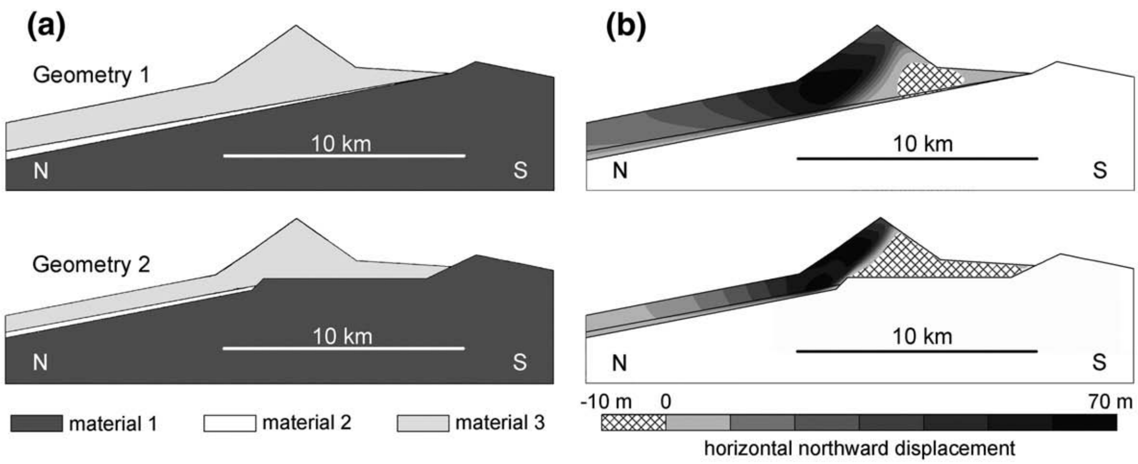

Fig. 13. Numerical model showing the possible effect of different basement morphologies on the evolution of Teide edifice. (a) Geometries of the models. Geometry 1 illustrates the case where Teide is built in the Icod landslide embayment and Geometry 2 where Teide is built on the Icod landslide headwall and Las Cañadas Caldera. (b) Modelling results indicating northerly directed horizontal displacement for each case. Negative values indicate zones with southward displacements.

Table 2
Material properties used for the numerical modelling of spreading of Teide volcano along a weak basal layer (values after Voight et al., 1983; Apuani et al., 2005; del Potro and Hürlimann, 2008, in press)

Material	Unit weight (kN/m^3)	E (GPa)	ν	c (kPa)	φ (°)
1	30	100	0.1	–	–
2	24	1	0.3	0	15
3	24	1	0.3	500	30

preliminary 2-D finite element models to assess the effects of basement influence, potential proto-Teide edifice morphology during the building stages of Teide and large edifice instabilities. Additionally, caldera collapses, flank vents, cryptodome intrusions, lava field morphologies and glacial erosion are also discussed.

6.1. The role of gravitational instability, erosion, intrusions and lava flows

6.1.1. Structural deformation – effects of basement topography

van Bemmelen (1949) and Borgia et al. (1990) were the first to argue that the load created by the accumulation of material on a volcanic edifice can result in elastic disequilibrium and generate edifice deformation if the substrate is weak. This normally occurs along weak sedimentary lithologies underlying volcanic products (van Wyk de Vries and Francis, 1997). On Teide, weak, destructured or mechanically collapsed volcanic materials from the end of the Diego Hernández and the beginning of the Teide cycles and the weak, clay-rich volcanic materials from the Icod avalanche (Navarro and Coello, 1989) could generate the same effect. Volcano spreading normally causes thrust and reverse faults along the foot of the edifice (van Bemmelen, 1949; van Wyk de Vries and Metala, 1998) and, although these have not been observed around Teide, it could be argued that the critical mass above which the volcano enters the thrusting phase (Borgia, 1994) has not been reached.

Márquez et al. (2008) suggest that this mechanism operates at Teide volcano and that it has formed the bulges. In their study they present a qualitative analysis of this hypothesis assuming that the basement of Teide is a landslide embayment, despite the strong evidence against it, and that there is a thin, very weak layer at the base of the edifice, described as the deposit of the Icod debris avalanche by Coello and Bravo (1989). Here we test this hypothesis in a quantitative analysis using 2-D finite element models (PLAXIS bv, 2006) of a north–south cross-section of Tenerife. We have developed two different models in order to assess the significance of the two different plausible paleo-topographies (Fig. 13a): (i) a landslide embayment – Geometry 1; and (ii) Las Cañadas Caldera and the Icod headwall – Geometry 2. All models are developed assuming a dry, elastic-plastic, very weak, homogeneous edifice with an extremely weak elastic–plastic basal unit, relaxing over a rigid, elastic media (Table 2).

Both models result in 'symmetric type deformation', following Cecchi et al. (2005), with maximum horizontal displacement values larger for Geometry 1, attributed to the greater volume of weak material infilling Icod (Fig. 13b). Geometrically, the deformation of Teide over Las Cañadas Caldera and the Icod landslide (Geometry 2) better reflects the current position of the bulge on the north-western flank (Fig. 13b). Also, Geometry 2 agrees with the maximum depth of the Icod valley infilling materials estimated by Coello and Bravo (1989) whereas in Geometry 1 it is almost doubled. Moreover, Geometry 2 shows the potential formation of a small bulge on the southern part of the edifice, which Ablay and Martí (2000) attribute to be the continuation of the Roques de García spur underneath the Teide–Pico Viejo formation. Geometry 2 results also show the potential generation of tensile stresses on the summit region which could have induced gräben collapse. When the models were run again without the weak basal layer in order to determine its significance, the results were almost identical.

It is important to note that the modelling results show that, in all cases, deformation achieved by this mechanism is almost one order of magnitude smaller than the current bulges, even for unrealistic low values of elastic parameters. Moreover, for Geometry 2 this hypothesis cannot solely be used to interpret the east–north-eastern bulge in a 3-dimensional context as it fails to describe the circular shape of the bulge: on plan-view, the curvature of the Icod headwall is concave with respect to an E–W direction whereas the north-western bulge is convex. This hypothesis is also rejected because no displacement on the edifice has been measured (Fernández et al., 2004, 2005).

6.1.2. Large vertical collapses

If Teide has suffered from one, or more, large vertical collapses during its evolution, these could be responsible for its morphology. If both bulges marked the extent of a pre-T-I vertical collapse of the central volcanic system, it would have a minimum surface area of

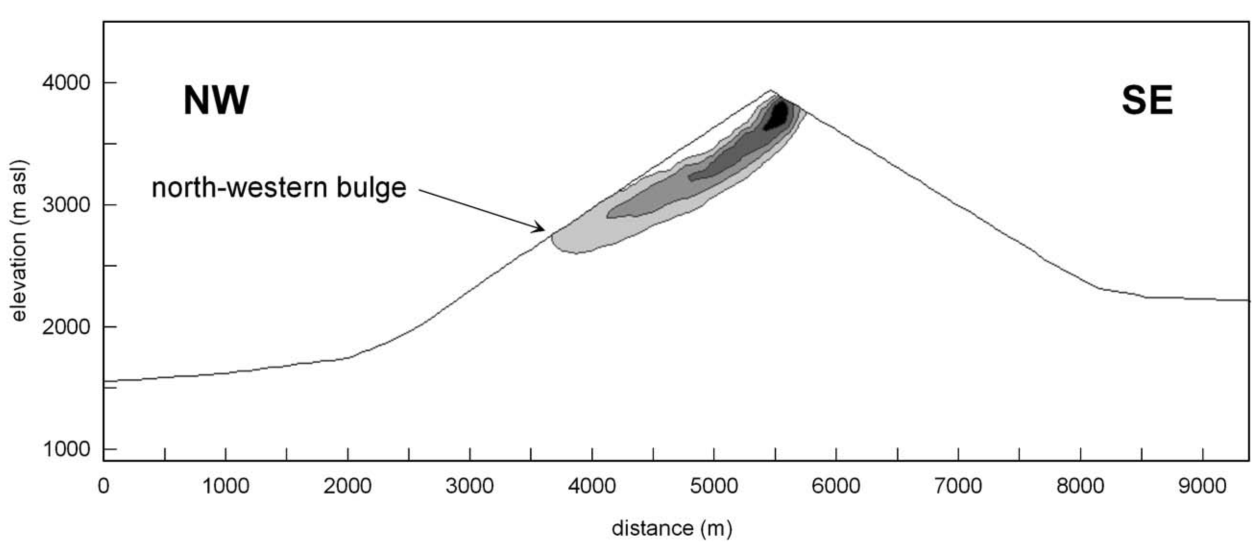

Fig. 14. Slope stability model results showing the geometry of a failure plane on a potential paleo-Teide slope. Results are given as 12.5% shear strain value contours from black (50%) decreasing to white (0). See Fig. 5, section B-B', for current topography.

4.5 km^2, which could correspond to a volume of ~2 km^3. If this collapse is also extended to the southern bulge the minimum estimated volume is doubled. However, large caldera collapses are largely overruled by the lack of volumetrically significant pyroclastic deposits and pit crater formation is mostly overruled by the large volume of magma withdrawal required. Additional evidence against a large vertical collapse mechanism can be seen in the slight geometrical overlap of both bulges on the northern flank.

6.1.3. Edifice slope instability

A range of sector and flank lateral collapse scenarios have been modelled numerically using the same 2-D finite element method (PLAXIS bv, 2006). Most scenarios are rejected, either because they are geomechanically unlikely, or geometrically impossible. In addition, the absence of landslide deposits on the upper slopes of the Icod valley argues strongly against this hypothesis. The only viable scenario is a 0.4 km^3 failure of the upper north-western paleo-flank (Fig. 14). In this numerical model of a possible sector collapse, Teide is modelled as a homogenous, elastic–plastic, dry cone. For this analysis, we assume an elastic modulus of 7.5 GPa and a Poisson's ratio of 0.3 to represent a weak elastic material (Voight, 2000). Shear strength parameters used, following Mohr–Coulomb, are an angle of internal friction of 30° and a cohesion of 200 kPa (e.g. Voight et al., 1983; Watters et al., 2000; Moon et al., 2005; del Potro and Hürlimann, 2008). For these input parameters, the failure plane with the lowest factor of safety (1.2) daylights at an elevation directly above the north-western bulge (~2700 m). Pseudo-static model results show that relatively small seismically-induced peak ground accelerations (0.08 g) could have triggered such a landslide. However, this mechanism alone fails to account for the Las Calvas volcaniclastic deposits.

6.1.4. Other hypotheses: crypto-dome, lava field and glacial erosion

The presence of the bulges, volcaniclastic deposits and domes along the foot of the Teide edifice (Aubert and Kieffer, 1996) might suggest the presence of cryptodome intrusions. Such events are known to cause extensive deformation to volcanic edifices forming prominent bulges and summit gräbens (e.g. Mt St Helens – Donnadieu and Merle, 1998). However, there is no evidence of dome intrusions

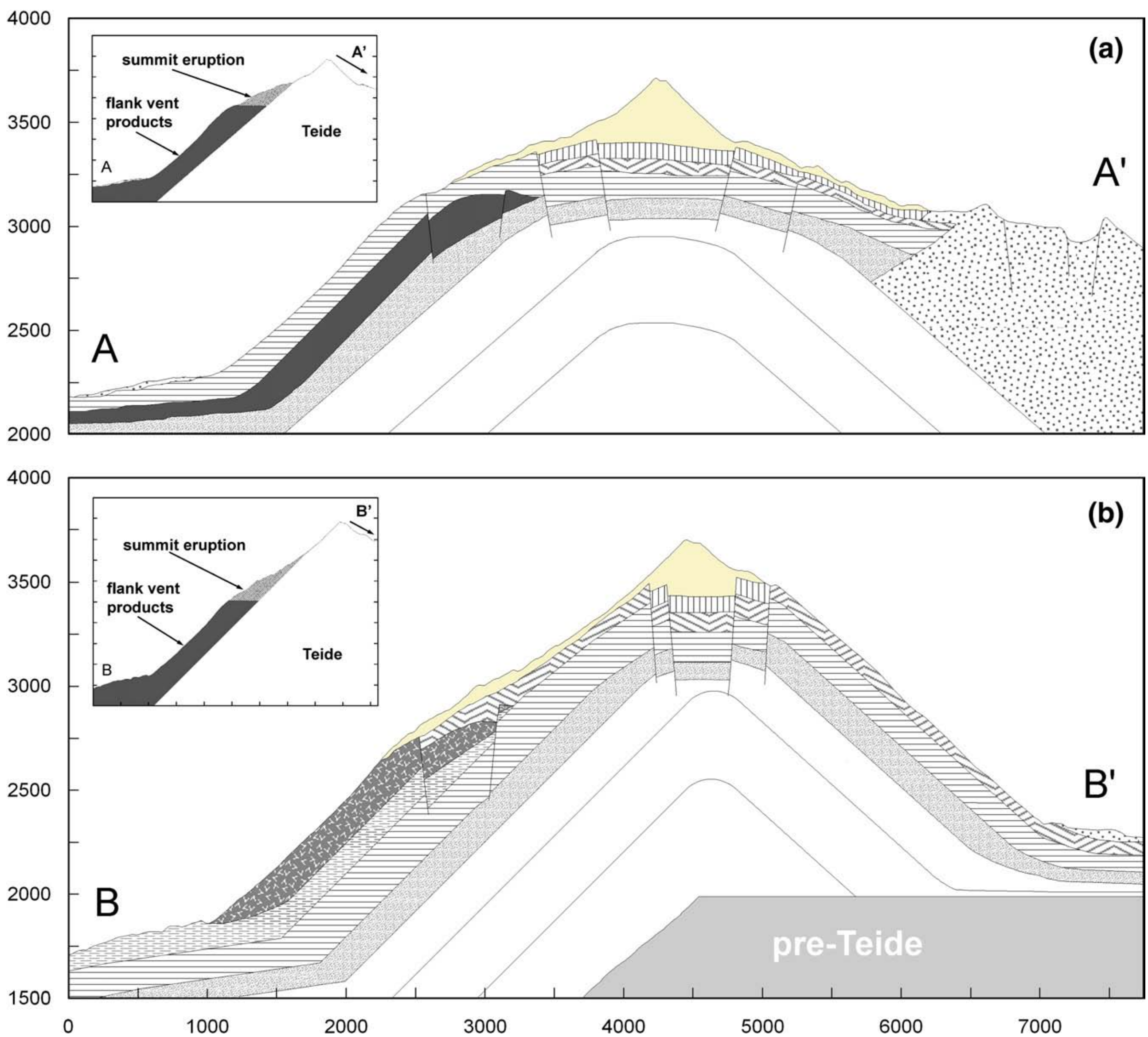

Fig. 15. Cross-sections of the Teide edifice showing (a) north-western bulge and (b) east–north-eastern bulge with schematic representations of the inferred relative positions of the identified geological units. See Fig. 3 for unit legend and the location of the cross-sections.

into the upper flanks of Teide edifice, nor is there evidence of high level intrusions on Las Cañadas Caldera wall during the three previous cycles of volcanism.

Summit-erupted, predominantly short lava flows overlain by rare, longer flows could be responsible for a convex-up change in slope at mid-elevation. There is, however, no physical reason why this mechanism should result in the development of the horizontality and constancy observed on both Teide bulges or why this mechanism would operate at only two locations.

It could also be argued that during the last glaciation Teide hosted a large glacier on its northern flank which caused the observed morphologies. However, the current morphology suggests that only a small glacier was present, on the horse-shoe shaped embayment on the upper northern flank, which accounts for the glacial and periglacial features currently observed. This glacier could have provided a water source for the phreatomagmatic activity during the formation of the Las Calvas volcaniclastics and the eruption of the east–north-eastern bulge domes/coulées.

6.2. The role of flank vents

A more plausible explanation for the formation of both bulges, which accounts for all the features previously described, is that they have a constructional origin: each bulge represents a flank vent that is now completely covered by overlying units (Figs. 12 and 15). Assuming the original slopes of Teide were ~30° (as observed on the southern flanks) the geometries of both bulges could represent the products of flank eruptions with a total volume of ~0.8 km^3. However, for these geometries to match the observed horizontality of the slope breaks along the bulges, the flank vents would have had to have undergone some vertical summit collapse. Two ~0.2 km^3 summit eruptions postdating the flank eruptions are estimated to have had sufficient volume to cover both flank vents and create the current morphology (inset Fig. 15). Following the model by Ablay and Martí (2000), both flank vents could have formed as a consequence of main chamber conduit blockage to Teide.

The Las Calvas Volcano (LCV), or “Volcán de Las Calvas del Teide” as given by Pérez-Torrado et al. (2004), currently buried forming the north-western bulge (Fig. 12), would have produced the Las Calvas volcaniclastics. This hypothesis suggests that post-T-I materials buried the flank vent (Fig. 15). The absence of T-K products on the upper slopes of Teide could imply that it was T-J. In such case, regardless of whether T-K was erupted from the LCV flank vent of from elsewhere on the northern flank of Teide, the stratigraphic relationship set by Ablay and Martí (2000) does not work here and T-J would be younger than T-K.

The eastern–north-eastern bulge vent (EBV) (Fig. 12) follows the alignment of the Pico Viejo–Teide summits, the summit gräben and the Dorsal Ridge. The generation of a summit-pit by vertical collapse of the east–north-eastern bulge flank vent could have promoted circumferential dykes through ring fractures which, constrained by the strong SW–NE regional tectonic trend, would have reached the surface above and below the summit collapse. Such mechanism explains the presence of T-I lavas near the summit region and lavas erupted from the domes/coulées along the break in slope.

7. Conclusions

The abnormal morphological features found on Teide volcano are a direct consequence of its complex structure. If our interpretation is correct, the presence of large, buried vents beneath both bulges suggests that flank vents other than Pico Viejo have formed. This consequently has significant implications for the location of future eruption vents and areas that might be affected. The presence of several feeding volcanic systems within the edifice could have generated a broader volume of hydrothermally altered material than a single vent. Unlike most vents along the base of Teide which are mainly phonolitic, flank vents have been more mafic in composition.

Our results reveal that the significance of explosive activity from the central edifice has been largely underestimated by previous workers. While most volcaniclastic deposits formed during the collapse of incandescent lava flow fronts, and, possibly, lava domes and lobes, there is clear evidence of phreatomagmatic activity on the north-western flank. However, the source of the large volumes of water required remains unresolved. We suggest that this could have come from a perched aquifer or a crater lake during the last stages of the last glaciation, which is not inconsistent with the stratigraphic position of the phreatomagmatic deposits. However, the possible existence of large amounts of hydrothermal water must also be considered. Notwithstanding its origin, if significant volumes of water were to be present during future eruptions, more phreatomagmatic activity could take place.

Detailed morphometric analysis, coupled with numerical modelling, supports the hypothesis of Martí et al. (1997), Ablay and Martí (2000) and Ablay and Hürlimann (2000) that the Teide edifice is built on the headwall of the Icod island flank collapse. The identification of new major eruption vents supports the previously identified “W”-geometry of the central axis system. The elongated nested summit collapses and the Las Calvas Volcano follow the Dorsal ridge lineation which, together with the location of Pico Viejo, could suggest that in the Teide area the Dorsal Ridge lineation has been more significant, despite the relatively recent phonolitic eruption of Montaña Blanca and most mafic activity taking place along the Santiago Ridge.

Until now, Teide's activity has been perceived as mainly effusive eruptions of mafic and lately phonolitic lavas, with volatile driven and phreatomagmatic explosive processes taking place on mainly phonolitic domes along the base of the edifice. We have identified alternative dynamics for explosive activity from the Teide edifice, involving the collapse of lava lobes and flows and the interaction of mafic lava and water in phreatomagmatic eruptions from large flank vents at mid-elevation. The explosive processes that have been recognised in this survey and the location of the various eruption vents should be taken into account in future hazard mitigation plans.

Acknowledgements

This research was partly funded by Cartográfica de Canarias S.A. (GRAFCAN) which also provided access to valuable geographical data sets. Hugh Tuffen is gratefully acknowledged for his help with petrographical analyses. We thank Robert J. Watters and John A. Stevenson for their valuable help in the field and for stimulating discussions at the early stages of this study. Alberto Ledesma is acknowledged for granting access to Plaxis 8x. Benjamin van Wyk de Vries and Claus Siebe are thanked for their careful reviews of the manuscript.

References

Ablay, G.J., Hürlimann, M., 2000. Evolution of the north flank of Tenerife by recurrent giant landslides. Journal of Volcanology and Geothermal Research 103, 135–159.

Ablay, G.J., Kearey, P., 2000. Gravity constraints on the structure and volcanic evolution of Tenerife, Canary Islands. Journal of Geophysical Research 105, 5783–5796.

Ablay, G.J., Martí, J., 2000. Stratigraphy, structure and volcanic evolution of the Pico Teide – Pico Viejo formation, Tenerife, Canary Islands. Journal of Volcanology and Geothermal Research 103, 175–208.

Ablay, G.J., Carroll, M.R., Palmer, M.R., Martí, J., Sparks, R.S.J., 1998. Basanite–phonolite lineages of the Teide Pico Viejo volcanic complex, Tenerife, Canary Islands. Journal of Petrology 39 (5), 905–936.

Alvarado, G.E., Soto, G.J., 2002. Pyroclastic flow generated by crater-wall collapse and outpouring of the lava pool of Arenal Volcano, Costa Rica. Bulletin of Volcanology 63, 557–568.

Ancochea, E., Fúster, J.M., Ibarrola, E., Cendrero, A., Coello, J., Hernán, F., Cantagrel, J.M., Jamond, C., 1990. Volcanic evolution of the island of Tenerife (Canary Islands) in the light of new K–Ar data. Journal of Volcanology and Geothermal Research 44, 231–249.

Ancochea, E., Cantagrel, J.M., Fúster, J.M., Huertas, M.J., Arnaud, N.O., 1998. Vertical and lateral collapses on Tenerife (Canary Islands) and other volcanic ocean islands: Comment. Geology 26 (9), 861–862.

Ancochea, E., Huertas, M.J., Cantagrel, J.M., Coello, J., Fúster, J.M., Arnaud, N., Ibarrola, E., 1999. Evolution of the Cañadas edifice and its implications for the origin of the Cañadas Caldera (Tenerife, Canary Islands). Journal of Volcanology and Geothermal Research 88 (3), 177–199.

Apuani, T., Corazzato, C., Cancelli, A., Tibaldi, A., 2005. Stability of a collapsing volcano (Stromboli, Italy): limit equilibrium analysis and numerical modelling. Journal of Volcanology and Geothermal Research 144 (1–4), 191–210.

Araña, V., 1971. Litología y estructura del Edificio Cañadas, Tenerife (Islas Canarias). Estudios Geológicos 27, 95–135.

Araña, V., Felpeto, A., Astiz, M., García, A., Ortíz, R., Abella, R., 2000. Zonation of the main volcanic hazards (lava flows and ash fall) in Tenerife, Canary islands. A proposal for a surveillance network. Journal of Volcanology and Geothermal Research 103 (1–4), 377–391.

Aubert, M., Kieffer, G., 1996. Evolution of a phonolitic dome deduced from geoelectrical and morphological data: the case of the Pico del Teide (Spain). Comptes Rendus De L'Academie Des Sciences Serie II Fascicule A-Sciences De La Terre Et Des Planetes 323 (8), 645–650.

Aubert, M., Kieffer, G., 1998. Graben sector slipping hypothesis on the north-east part of the Las Cañadas caldera (Teide, Tenerife, Spain) – Geophysical and morphological aspects. Comptes Rendus De L'Academie Des Sciences Serie II Fascicule A-Sciences De La Terre Et Des Planetes 326 (2), 87–92.

Behncke, B., Calvari, S., Giammanco, S., Neri, M., Pinkerton, H., 2008. Pyroclastic density currents resulting from the interaction of basaltic magma with hydrothermally altered rock: an example from the 2006 summit eruptions of Mount Etna, Italy. Bulletin of Volcanology 70 (10), 1249–126891.

Borgia, A., 1994. Dynamic basis of volcanic spreading. Journal of Geophysical Research 99, 17791–17804.

Borgia, A., Burr, J., Montero, L.D., Morales, W., Alvarado, G.E., 1990. Fault propagation folds induced by gravitational failure and slumping of the Central Costa Rica Volcanic Range: Implications for large terrestrial and Martian volcanic edifices. Journal of Geophysical Research 95, 14357–14382.

Brown, R.J., Branney, M.J., 2004. Event-stratigraphy of a caldera-forming ignimbrite eruption on Tenerife: the 273 ka Poris Formation. Bulletin of Volcanology 66 (5), 392–416.

Bryan, S.E., Martí, J., Cas, R.A.F., 1998. Stratigraphy of the Bandas del Sur Formation: an extracaldera record of Quaternary phonolitic explosive eruptions from the Las Cañadas edifice, Tenerife (Canary Islands). Geological Magazine 135 (5), 605–636.

Bryan, S.E., Cas, R.A.F., Marti, J., 2000. The 0.57 Ma plinian eruption of the Granadilla Member, Tenerife (Canary Islands): an example of complexity in eruption dynamics and evolution. Journal of Volcanology and Geothermal Research 103 (1–4), 209–238.

Camacho, A.G., Viera, R., De Toro, C., 1991. Microgravimetric model of the Las Cañadas caldera (Tenerife). Journal of Volcanology and Geothermal Research 47, 75–88.

Cantagrel, J.M., Arnaud, N.O., Ancochea, E., Fúster, J.M., Huertas, M.J., 1999. Repeated debris avalanches on Tenerife and genesis of Las Cañadas caldera wall (Canary Island). Geology 27 (8), 739–742.

Carracedo, J.C., 1994. The Canary Island: an example of structural control on the growth of large oceanic-island volcanoes. Journal of Volcanology and Geothermal Research 60, 225–241.

Carracedo, J.C., 1999. Growth, structure, instability and collapse of Canarian volcanoes and comparisons with Hawaiian volcanoes. Journal of Volcanology and Geothermal Research 94 (1–4), 1–19.

Carracedo, J.C., Paterne, M., Guillou, H., Pérez-Torrado, F.J., Paris, R., Rodríguez Badiola, E., Hansen, A., 2003. Dataciones radiométricas (14C y K/Ar) del Teide y el Rift Noroeste, Tenerife, Islas Canarias. Estudios Geológicos 59, 15–29.

Cecchi, E., van Wyk de Vries, B., Lavest, J.M., 2005. Flank spreading and collapse of weak-cored volcanoes. Bulletin of Volcanology 67 (1), 72–91.

Coello, J., Bravo, T., 1989. Lineamientos volcano-tectónicos en la región central de Tenerife. In: Araña, V., Coello, J. (Eds.), Los volcanes y la caldera del Parque nacional del Teide (Tenerife, Islas Canarias). I.C.O.N.A, Madrid, pp. 127–136.

Concha-Dimas, A., 2004. Numerical Modeling in understanding catastrophic collapse at Pico de Orizaba, Mexico. Ph.D. Thesis, University of Nevada, Reno.

Coppo, N., Schnegg, P.-A., Heise, W., Costa, R., Falco, P., 2006. Multiple caldera collapse processes inferred from shallow electrical prints: example of the Las Cañadas caldera, Tenerife, Canary Islands, IAGA WG 1.2 on Electromagnetic Induction in the Earth. Extended Abstract 18 Workshop, El Vendrell, Spain, pp. 17–23.

del Potro, R., Hürlimann, M., 2008. Geotechnical classification and characterisation of materials for stability analyses of large volcanic slopes. Engineering Geology 98, 1–17.

del Potro and Hürlimann, in press. The decrease in the shear strength of volcanic materials with argillic hydrothermal alteration, insights from the summit region of Teide stratovolcano, Tenerife. Engineering Geology. doi: 10.1016/j.enggeo.2008.09.005.

Donnadieu, F., Merle, O., 1998. Experiments on the indentation process during cryptodome intrusions: new insights into Mount St Helens deformation. Geology 26, 79–82.

ESRI, 2005. ArcGIS 9: what is ArcGIS 9.1? ESRI, Redlands, California. 123 pp.

Farrujia, I., Velasco, J.L., Fernández, J., Martín, M.C., 2004. Evolución del nivel freático en la mitad oriental del acuífero de las Cañadas del Teide. Cuantificación de parámetros hidrogeológicos. VIII Simposio de Hidrogeología, vol. XXVII. Asociación Española de Hidrogeólogos, Zaragoza, pp. 131–142.

Fernández, J., González-Matesanz, F.J., Prieto, J.F., Rodríguez-Velasco, G., Staller, A., Alonso-Medina, A., Charco, M., 2004. GPS monitoring in the N–W part of the volcanic island of Tenerife, Canaries, Spain: strategy and results. Pure and Applied Geophysics 161 (7), 1359–1377.

Fernández, J., Romero, R., Carrasco, D., Tiampo, K.F., Rodríguez-Velasco, G., Aparicio, A., Araña, V., González-Matesanz, F.J., 2005. Detection of displacements on Tenerife Island, Canaries, using radar interferometry. Geophysical Journal International 160 (1), 33–45.

Fúster, J.M., Araña, V., Brandle, J.L., Navarro, M., Alonso, U., Aparicio, A., 1968. Geología y volcanología de las islas Canarias: Tenerife. Instituto 'Lucas Mallada'. CSIC, Madrid. 218 pp.

García, A., Vila, J., Ortiz, R., Macià, R., Sleeman, R., Marrero, J.M., Sánchez, N., Tárraga, M., Correig, A.M., 2006. Monitoring the Reawakening of Canary Islands' Teide Volcano. EOS, Transactions – American Geophysical Union 87 (6), 61–65.

Gottardi, G., 1989. The genesis of zeolites. European Journal of Mineralogy 1 (4), 479–487.

Gottsmann, J., Wooller, L., Martí, J., Fernández, J., Camacho, A.G., González, P.J., García, A., Rymer, H., 2006. New evidence for the reawakening of Teide volcano. Geophysical Research Letters 33 (20) Art. No. L20311.

Guest, J.E., Kilburn, C.R.J., Pinkerton, H., Duncan, A.M., 1987. The evolution of lava flow-fields: observations of the 1981 and 1983 eruptions of Mount Etna, Sicily. Bulletin of Volcanology 49 (3), 527–540.

Huertas, M.J., Ancochea, E., Cantagrel, J.M., Coello, J., Fúster, J.M., Ibarrola, E., 1994. Un episodio volcánico pre-Cañadas en la Isla de Tenerife. Geogaceta 15, 113–116.

Hürlimann, M., Martí, J., Ledesma, A., 2000. Mechanical relationship between catastrophic volcanic landslides and caldera collapses. Geophysical Research Letter 27 (16), 2393–2396.

López, D.L., Williams, S.N., 1993. Catastrophic volcanic collapse: relation to hydrothermal processes. Science 260, 1794–1796.

López, I., 2002. Origin of Las Cañadas, Tenerife, Spain. Ms. thesis, Technical University of Catalonia, 55 pp.

Márquez, A., Lopez, I., Herrera, R., Martín-González, F., Izquierdo, T., Carreño, F., 2008. Spreading and potential instability of Teide volcano, Tenerife, Canary Islands. Geophysical Research Letters 35 (5).

Martí, J., Gudmundsson, A., 2000. The Las Cañadas caldera (Tenerife, Canary Islands): an overlapping collapse caldera generated by magma–chamber migration. Journal of Volcanology and Geothermal Research 103, 161–173.

Martí, J., Mitjavila, J., Araña, V., 1994. Stratigraphy, structure and geochronology of the Las Cañadas caldera (Tenerife, Canary Island). Geological Magazine 131 (6), 715–727.

Martí, J., Ablay, G.J., Bryan, S., 1996. The Canary Islands: An example of structural control on the growth of large oceanic-island volcanoes – Comment. Journal of Volcanology and Geothermal Research 72 (1–2), 143–149.

Martí, J., Hürlimann, M., Ablay, G.J., Gudmundsson, A., 1997. Vertical and lateral collapses on Tenerife (Canary Islands) and other volcanic ocean islands. Geology 25 (10), 879–882.

Moon, V., Bradshaw, J., Smith, R., de Lange, W., 2005. Geotechnical characterisation of stratocone crater wall sequences, White Island Volcano, New Zealand. Engineering Geology 81 (2), 146–178.

Navarro, J.M., Coello, J., 1989. Depressions originated by landslide processes in Tenerife. Abstract ESF Meeting on Canarian Volcanism, pp. 150–152.

Ortiz, R., Araña, V., Astiz, M., García, A., 1986. Magnetotelluric study of the Teide (Tenerife) and Timanfaya (Lanzarote) volcanic areas. Journal of Volcanology and Geothermal Research 30, 357–377.

Paul, A., Gratier, J.P., 1987. A numerical model for simulating deformation of Mount St. Helens Volcano. Journal of Geophysical Research 92 (B10), 10299–10312.

Pérez-Torrado, F.J., Martí, J., Queralt, I., Mangas, J., 1995. Alteration processes of the Roque Nublo Ignimbrites (Gran-Canaria, Canary-Islands). Journal of Volcanology and Geothermal Research 65 (3–4), 191–204.

Pérez-Torrado, F.J., Carracedo, J.C., Paris, R., Hansen, A., 2004. Descubrimiento de depósitos freatomagmáticos en las laderas septentrionales del estratovolcán Teide (Tenerife, Islas Canarias): relaciones estratigráficas e implicaciones volcánicas. Geo-Temas 6 (1), 163–166.

Pinkerton, H., 1987. Factors affecting the morphology of lava flows. Endeavour 11 (2), 73–79.

PLAXIS bv, 2006. PLAXIS v8 user's manual. PLAXIS bv, DELFT, Netherlands.

Pous, J., Heise, W., Schnegg, P.A., Muñoz, G., Martí, J., Soriano, C., 2002. Magnetotelluric study of the Las Cañadas caldera (Tenerife, Canary Islands): structural and hydrogeological implications. Earth and Planetary Science Letters 204 (1–2), 249–263.

Quidelleur, X., Gillot, P.Y., Soler, V., Lefevre, J.C., 2001. K/Ar dating extended into the last millennium: application to the youngest effusive episode of the Teide volcano (Spain). Geophysical Research Letters 28 (16), 3067–3070.

Reid, M.E., Sisson, T.W., Brien, D.L., 2001. Volcano collapse promoted by hydrothermal alteration and edifice shape, Mount Rainier, Washington. Geology 29 (9), 779–782.

Ridley, W.I., 1970. The petrology of the Las Cañadas Volcanoes, Tenerife, Canary Islands. Contributions to Mineralogy and Petrology 26, 124–160.

Ridley, W.I., 1971. The origin of some collapse structures in the Canary Islands. Geology Magazine 108, 477–484.

Rose, W.I., Pearson, T., Bonis, S., 1976. Nuée ardente eruption from the foot of a dacite lava flow, Santiaguito volcano. Guatemala Bulletin of Volcanology 40 (1), 23–38.

Russo, G., Giberti, G., Sartoris, G., 1997. Numerical modeling of surface deformation and mechanical stability of Vesuvius volcano, Italy. Journal of Geophysical Research 102 (B11), 24785–24800.

Soler, V., Castro-Almazán, J.A., Vinas, R.T., Eff-Darwich, A., Sánchez-Moral, S., Hillaire-Marcel, C., Farrujia, I., Coello, J., de la Nuez, J., Martín, M.C., Quesada, M.L., Santana, E., 2004. High CO2 levels in boreholes at El Teide volcano complex (Tenerife, Canary Islands): Implications for volcanic activity monitoring. Pure and Applied Geophysics 161 (7), 1519–1532.

Tibaldi, A., 2004. Major changes in volcano behaviour after a sector collapse: insights from Stromboli, Italy. Terra Nova 16 (1), 2–8.

Tibaldi, A., Corazzato, C., Apuani, T., Cancelli, A., 2003. Deformation at Stromboli volcano (Italy) revealed by rock mechanics and structural geology. Tectonophysics 361 (3–4), 187–204.

van Bemmelen, R.W., 1949. The Geology of Indonesia. Government Printing Office, La Hague.

van Wyk de Vries, B., Francis, P.W., 1997. Catastrophic collapse at stratovolcanoes induced by gradual volcano spreading. Nature 387, 387–390.

van Wyk de Vries, B., Metala, R., 1998. Styles of volcano-induced deformation: numerical models of substratum flexure, spreading and extrusion. Journal of Volcanology and Geothermal Research 81, 1–18.

van Wyk de Vries, B., Kerle, N., Petley, D., 2000. Sector collapse forming at Casita volcano, Nicaragua. Geology 28 (2), 167–170.

Vieira, R., Toro, C., Araña, V., 1986. Microgravimetric survey in the Caldera of Teide, Tenerife, Canary Islands. Tectonophysics 130, 249–257.

Voight, B., 2000. Structural stability of andesite volcanoes and lava domes. Philosofical Transactions of Royal Society of London, A 358, 1663–1703.

Voight, B., Janda, R.J., Glicken, H., Douglass, P.M., 1983. Nature and mechanics of the Mount St Helens rockslide-avalanche of 18 May 1980. Géotechnique 33 (3), 243–273.

Walter, T.R., Schmincke, H.U., 2002. Rifting, recurrent landsliding and Miocene structural reorganization on NW-Tenerife (Canary Islands). International Journal of Earth Sciences 91 (4), 615–628.

Walter, T.R., Troll, V.R., Cailleau, B., Belousov, A., Schmincke, H.U., Amelung, F., Von der Bogaard, P., 2005. Rift zone reorganization through flank instability in ocean island volcanoes: an example from Tenerife, Canary Islands. Bulletin of Volcanology 67 (4), 281–291.

Watters, R.J., Zimbelman, D.R., Bowman, S.D., Crowley, J.K., 2000. Rock mass strength assessment and significance to edifice stability, Mount Rainier and Mount Hood, Cascade Range volcanoes. Pure and Applied Geophysics 157 (6–8), 957–976.

Watts, A.B., Masson, D.G., 1995. A giant landslide on the north flank of Tenerife, Canary Islands. Journal of Geophysical Research 100 (B12), 24,487–24,498.

Zimbelman, D.R., Watters, R.J., Firth, I.R., Breit, G.N., Carrasco-Nuñez, G., 2004. Stratovolcano stability assessment methods and results from Citlaltepetl, Mexico. Bulletin of Volcanology 66 (1), 66–79.