The late Quaternary Diego Hernandez Formation, Tenerife: Volcanology of a complex cycle of voluminous explosive phonolitic eruptions


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Abstract

The Diego Hernandez Formation (DHF; 600–ca. 180 ka) represents the products of the most recent complete cycle of phonolitic explosive volcanism on Tenerife (Canary Islands, Spain). We provide a revised and detailed stratigraphy, new 40Ar/39Ar and (U–Th)/He age determinations for major eruptive units, a summary of new chemical data and an overview of the key characteristics of the cycle, including volume estimates, dispersal patterns, eruption styles, phreatomagmatic influences and caldera collapse episodes. The complex stratigraphy of the DHF is divided into 20 named members, each representing a major eruption, as well as numerous unnamed members of limited present-day exposure. The major eruptions are represented by the Fortaleza (370 ka), Roque (347 ka, 3 km³), Aldea (319 ka, 3 km³), Fasnia (309 ka, 13 km³), Poris (268 ka, 3.5 km³), Arafo (4 km³), Caleta (223 ka, 3.5 km³) and Abrigo (between 196 and 171 ka, 20 km³) Members. The Aldea, Fasnia and Poris Members consist of highly complex successions of plinian fall, surge and flow deposits and several of the eruptions produced widespread and internally complex ignimbrite sheets. Phreatomagmatism occurred most frequently in the opening phase of the eruptions but also recurred repeatedly throughout many of the sequences. Inferred sources of water include a shallow caldera lake and groundwater, and intermittent phreatomagmatic activity was an important influence on eruption style. Another important factor was conduit and vent instability, which frequently loaded the eruption column with dense lithic debris and occasionally triggered column collapse and ignimbrite formation. Most of the major DHF eruptions were triggered by injection of mafic magma into existing phonolitic magma bodies. Two phonolitic magma types were available for eruption during the lifetime of the DHF, but each was dominant at different times. The results presented here support a caldera collapse rather than a landslide model for the origin of the Las Cañadas Caldera, although the evolution of the caldera is evidently more complex and incremental than first thought.

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Keywords: Tenerife; plinian; phonolite; ignimbrite; caldera; phreatomagmatism

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1. Introduction

Explosive eruptions involving felsic magma volumes of the order of 1 km$^3$ or more typically produce plinian fallout and pyroclastic density currents (PDCs: flows and surges) with great destructive potential. Tenerife has a complex Quaternary history of explosive phonolitic eruptions, with an aggregate volume of the order of 100 km$^3$ dense rock equivalent (DRE). Some of these eruptions covered 90% of the island with PDC deposits and were accompanied by caldera formation and lateral collapse episodes. The island has a large residential population (655,000), a well-developed rural and civic infrastructure, and has seen an explosive growth in tourism and associated industries over the past few decades. Consequently, a precise understanding of the Quaternary geologic record on Tenerife is a high priority, and a large body of geochronological, volcanological, petrological and geochemical data on the phonolitic pyroclastic rocks has been collected in recent years (Martí et al., 1990, 1994; Ablay et al., 1995, 1998; Bryan et al., 1998, 2002; Edgar et al., 2002; Brown et al., 2003; Brown and Branney, 2004a,b; Pittari et al., 2005, 2006; see also the volumes edited by Martí and Mitjavila, 1995, and Martí and Wolff, 2000).

Conflicting interpretations remain in two critical areas: the origin of the central Las Cañadas depression (caldera versus lateral collapse scar; see Ancochea et al., 1990; Carracedo, 1994; Martí et al., 1994; Watts and Masson, 1995; Martí et al., 1997; Bryan et al., 1998; Ancochea et al., 1998, 1999; Cantagrel et al., 1999), and details of the very complex stratigraphy of the pyroclastic deposits (Bryan et al., 1998, 2002; Edgar et al., 2002; Brown et al., 2003; Brown and Branney, 2004a,b). The present paper is a summary of the event stratigraphy, geochronology and geochemistry of the Diego Hernández Formation (DHF), which represents the last complete major cycle of explosive phonolitic activity on Tenerife. It incorporates revisions to the stratigraphic schemes and interpretations presented by Bryan et al. (1998) and Brown et al. (2003), new $^{40}$Ar/$^{39}$Ar and (U–Th)/He age determinations, and a synthesis of chemical data for some 350 samples. We show that the DHF cycle began with minor phonolitic eruptions, with parallels to Holocene activity from Las Cañadas (Ablay et al., 1995). If indeed a similar phonolitic cycle is now beginning, as proposed by Martí et al. (1994), then our study has long-term predictive value.

2. Geologic background

Tenerife (Fig. 1) is the largest of the Canary Islands. The basal subaerial portion, the Old Basaltic Series, consists mostly of lavas of at least three mafic alkaline shield volcanoes constructed between 12 and 3.9 Ma (Fúster et al., 1968; Ancochea et al., 1990; Martí et al., 1995, Thirlwall et al., 2000; Guillou et al., 2004), and now exposed as eroded massifs in the extremities of the island. These are overlain by the Las Cañadas edifice (Araña, 1971), a large composite stratovolcano consisting of a dominantly mafic to intermediate Lower Group (3.5–2.2 Ma), and an Upper Group (1.6–0.18 Ma) that includes the products of three basaltic-to-phonolitic volcanic cycles, represented by the Ucanca, Guajara, and Diego Hernandez formations. In the Las Cañadas caldera wall, the three formations are separated by major erosional disconformities, interpreted as the results of caldera collapse and associated lateral collapse episodes that terminated each cycle (Martí et al., 1994, 1997). Stratigraphically equivalent major disconformities outside the caldera are due to extended periods of non-deposition, when phonolitic eruptions of wide dispersal did not occur following cycle-ending collapse episodes. Basaltic eruptive activity, contemporaneous with growth of the Las Cañadas edifice, was plentiful in both the summit areas and flanks of Tenerife, and has continued into the historic period. The two main zones of basaltic eruptions are the northwestern Santiago Rift Zone and the northeastern Dorsal Rift Zone (Fig. 1). Within the summit caldera of Las Cañadas are situated the twin stratocones of Teide (3718 m) and Pico Viejo (3103 m), along with numerous satellite vents, all formed since the last caldera collapse at ca. 0.18 Ma (Ridley, 1970, 1971; Mitjavila and Villa, 1993; Ablay et al., 1998). The most recent eruptions of phonolitic magma occurred from this complex at $\leq$ 2 ka (Ablay et al., 1995; Ablay and Martí, 2000). Similarities between the Teide–Pico Viejo record and the basal portions of earlier cycles (Martí et al., 1994, Ablay et al., 1995, and below) suggest the Holocene phonolitic activity represents the start of a fourth Quaternary explosive cycle with the potential to produce future catastrophic caldera-forming events.

3. Overview of DHF stratigraphy

The Diego Hernandez Formation (DHF) represents the youngest of the three complete magmatic cycles in the Upper Group. Following Martí et al. (1994), the DHF includes all volcanic units erupted from the Las Cañadas caldera (LCC) that lie stratigraphically above the Granadilla Member of the underlying Guajara Formation (Bryan et al., 1998, 2000), up to and including the Abrigo Member (Fig. 2). The Granadilla eruption was the terminal caldera-forming event of
the Guajara cycle, and has been dated by $^{40}\text{Ar}/^{39}\text{Ar}$ at $600\pm 18$ ka (Brown et al., 2003). In the type section at the easternmost part of the Las Cañadas caldera wall (hereafter referred to as the DH wall, Fig. 1), the DHF contains several sedimentary interbeds and minor phonolitic pumice deposits near the base, and inter-fingers with mafic scoria beds and lava flows of the Dorsal Series, erupted from vents located near the intersection of the Dorsal Ridge with the DH wall. The type section infills the head region of the Orotava valley, a large collapse scar in the north flank of Tenerife (Fig. 1). In the southern coastal zone of Tenerife, known as the Bandas del Sur, members of the DHF are typically separated by palaeosols, erosion horizons, or, occasionally, coarse fluvial gravels. Wolff et al. (2000) subdivided the principal phonolitic units of the DHF into three chemostratigraphic sequences, DHF I (oldest) to DHF III (youngest). Here we recognise another subdivision beneath DHF I in the type section, the basal sequence (DHFbs), which is dominated by sediments and mafic lavas. A comparison between the present and previous stratigraphic schemes for the Upper Group is provided in Fig. 2.

In this paper, a member is defined as a sequence of volcanic deposits which is bounded by palaeosols or weathered horizons and an eruption is defined as a sequence of events which produces a member. This usage follows established practice for mapping of volcanic areas, where members are separated by significant time breaks and a formation consists of one or more such related members. Members are given locality-based names and are subdivided into units and subunits on the basis of facies characteristics and inferred mode of deposition. Fall and surge units are labelled alphabetically from base to top and subunits have been labelled alphanumerically. Ignimbrite units have been given locality-based names, although where only one ignimbrite unit has been identified within a member, it is referred to by the member name (e.g. the Caleta ignimbrite).

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**Fig. 1.** Map of Tenerife showing the present-day distribution of the Diego Hernandez Formation (in black) and other major stratigraphic subdivisions. Note: (1) the inferred source area of the DHF in the eastern part of the Las Cañadas caldera complex and its subsequent burial by products of the Teide–Pico Viejo Formation; (2) the location of the two DHF caldera wall sequences: the DH wall to the east and La Fortaleza to the north, which are separated by a gap (El Portillo); (3) the three large valleys bounded by steep scarps produced by major landslides that have punctuated the history of Tenerife; (4) the remnants of the Old Basaltic shield exposed in the three corners of the island; and (5) the two main rift zones along which flank basaltic volcanism has been concentrated (DRZ — Dorsal Rift Zone, SRZ — Santiago Rift Zone). Co-ordinates are U.T.M.
Fig. 2. Comparison between this study and previous stratigraphic schemes for the phonolitic pyroclastic succession of Tenerife (basaltic units not shown). *Sub-Fasnia M. includes the Cabezon, Tarasca, Guirres, Espigón, Tosca, Tarta and Taco Members, although their stratigraphic relationship to the Aldea and Roque Members and to each other is unknown. CDR — Caldera del Rey, Fm. — Formation, Ig. — Ignimbrite, M. — Member, P.C. — Piroclastos de Caida (Sp. pyroclastic fall deposit), Pum. — Pumice, u. d. — unpublished data. [Guajara Formation stratigraphy from J. Middleton (unpubl. data)].
Brown et al. (2003) recently proposed a stratigraphy for the DHF and part of the Guajara Formation based on mapping of the lower southeastern slopes. Our DHF stratigraphy is generally similar to, but more detailed than, that of Brown et al. (2003), with the following differences:

(1) Brown et al. (2003) gave formation status to the products of individual eruptions in their Bandas del Sur Group (Fig. 2). However, the division of the Las Cañadas Edifice into an Upper and Lower Group and the division of the Upper Group into three formations was established by Marti et al. (1994) on the basis of geologic relations in the caldera wall, and has been followed by most subsequent workers (Bryan et al., 1998, 2000; Wolff et al., 2000). Because we have correlated Bandas del Sur deposits with their equivalents in the Las Cañadas caldera wall, we retain the overall stratigraphic framework of Marti et al. (1994) in which each recognisable volcanic cycle bounded by major disconformities is afforded formation status, and mappable unit packages within a formation that can be interpreted as the products of single eruptions are given member status. In our scheme, the Bandas del Sur Group of Brown et al. (2003) consists of products of the Guajara and Diego Hernandez Formations, both of which are included in the Upper Group of Marti et al. (1994).

(2) The Aldea and Fasnia Members are considerably more complex than the descriptions by Brown et al. (2003) of the corresponding units. We also recognise the products of at least 6 (based on the maximum number seen in an individual section), and as many as 15 (based on chemical stratigraphy) plinian eruptions between the Caleta and Abrigo Members, rather than the two noted by Brown et al. (2003) between their La Caleta and Abrigo Formations.

(3) Numerous minor eruptive units, which cannot be recognized at more than a few exposures or are of uncertain stratigraphic position, occur beneath the Aldea Member and between major members of the DHF.

These and other new results, including Ar/Ar ages (Table 1), detailed unit descriptions, and erupted volumes (Table 2) are given in the remainder of the paper. We present correlations and composite stratigraphic sections of the major members (Figs. 3, 4), new isopach maps for plinian fallout deposits and distribution maps for ignimbrites (Fig. 5), and summarise the new chemical data (Fig. 6).

4. Geochronology

Prior attempts to date DHF units include the K/Ar studies of Mitjavila (1990), Ancochea et al. (1990, 1995) and Bryan et al. (1998). The K/Ar dates are often inconsistent with stratigraphy, suggesting that they may be affected by excess argon or the presence of xenocrysts and the uncertainties associated with them are often too large to resolve repose periods between major eruptions. In general, Ar/Ar determinations on alkali feldspars are preferred for dating young felsic volcanic rocks. Mitjavila and Villa (1993) provided the first DHF Ar/Ar age, on the Abrigo Member, of 183 ± 8 ka (note that all uncertainties reported or quoted in this

Table 1

<table>
<thead>
<tr>
<th>Member and unit</th>
<th>Sample number</th>
<th>40Ar/39Ar isochron age (ka)</th>
<th>40Ar/39Ar weighted mean age (ka)</th>
<th>Preferred (U-Th)/He age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abrigo, upper flow unit</td>
<td>TF00-153N*</td>
<td>188 ± 12</td>
<td>197 ± 9 [n=8(13)]</td>
<td>196 ± 6 [n=1]</td>
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<tr>
<td>Abrigo, upper flow unit</td>
<td>TF00-178N</td>
<td>212 ± 19</td>
<td>196 ± 8 [n=9(14)]</td>
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<tr>
<td>Batista fallout</td>
<td>TF00-9</td>
<td>224 ± 20</td>
<td>234 ± 7 [n=12(13)]</td>
<td>234 ± 7</td>
</tr>
<tr>
<td>Poris, Abona ignimbrite</td>
<td>TF00-17</td>
<td>269 ± 18</td>
<td>285 ± 7 [n=13(14)]</td>
<td>268 ± 8 [n=4]</td>
</tr>
<tr>
<td>Poris, Unit B fallout</td>
<td>TF00-37*</td>
<td>No isochron</td>
<td>268 ± 8 [n=10(12)]</td>
<td></td>
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<tr>
<td>Fasnia, Santo ignimbrite</td>
<td>TF99-89*</td>
<td>324 ± 9</td>
<td>313 ± 8 [n=10(11)]</td>
<td>309 ± 6 [n=1]</td>
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<tr>
<td>Fasnia, Subunit F4 fallout</td>
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<td>No isochron</td>
<td>305 ± 8 [n=10(11)]</td>
<td></td>
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<td>Aldea, Tajao ignimbrite</td>
<td>TF00-117</td>
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<td>319 ± 7 [n=11(11)]</td>
<td>319 ± 5</td>
</tr>
<tr>
<td>Aldea, lower plinian</td>
<td>TF00-73</td>
<td>334 ± 5</td>
<td>320 ± 8 [n=9(12)]</td>
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</tr>
<tr>
<td>Roque fallout</td>
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<td>351 ± 10</td>
<td>347 ± 8 [n=9(12)]</td>
<td>324 ± 23 [n=2]</td>
</tr>
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Table 2
Summary of volume estimates for the major members of the DHF, with complex members broken down into three deposit types. Refer to text for explanation of minimum and maximum values. The estimates of previous studies are shown for comparison.

<table>
<thead>
<tr>
<th>Member</th>
<th>This study</th>
<th>Previous estimates</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_{\text{min}}$ (km$^3$)</td>
<td>$V_{\text{max}}$ (km$^3$)</td>
<td>$V_{\text{DRE(max)}}$ (km$^3$)</td>
</tr>
<tr>
<td>Abrigo</td>
<td>1.8</td>
<td>–</td>
<td>~20</td>
</tr>
<tr>
<td></td>
<td>–</td>
<td>~25</td>
<td>~5</td>
</tr>
<tr>
<td>Benjos</td>
<td>–</td>
<td>~5</td>
<td>~1</td>
</tr>
<tr>
<td>Hidalga</td>
<td>–</td>
<td>~5</td>
<td>~1</td>
</tr>
<tr>
<td>Socorro</td>
<td>1.9</td>
<td>4.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Batista</td>
<td>0.8</td>
<td>10.1</td>
<td>2.0</td>
</tr>
<tr>
<td>Caleta</td>
<td>1.5</td>
<td>10.1</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ignimbrite</td>
<td>0.13</td>
<td>0.3</td>
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<tr>
<td></td>
<td>Ash/surge</td>
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<td>–</td>
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<td></td>
<td>Plinian fall</td>
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<td>Arafo</td>
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<td>18.6</td>
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<td>2.9</td>
<td>18.4</td>
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<td>Poris</td>
<td>2.7</td>
<td>12.4</td>
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<td></td>
<td>Ignimbrite</td>
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<td>5.5</td>
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<td></td>
<td>Ash/surge</td>
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<td></td>
<td>Plinian fall</td>
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<td>6.7</td>
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<td>Fasnia</td>
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<td>62.0</td>
<td>13.3</td>
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<tr>
<td></td>
<td>Ignimbrite</td>
<td>1.2</td>
<td>11.2</td>
</tr>
<tr>
<td></td>
<td>Ash/surge</td>
<td>0.15</td>
<td>0.23</td>
</tr>
<tr>
<td></td>
<td>Plinian fall</td>
<td>12.2</td>
<td>50.6</td>
</tr>
<tr>
<td>Aldea</td>
<td>–</td>
<td>~13.5</td>
<td>3.1</td>
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<tr>
<td></td>
<td>Ignimbrite</td>
<td>–</td>
<td>&lt;1</td>
</tr>
<tr>
<td></td>
<td>Ash/surge</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Plinian fall (A)</td>
<td>4.8</td>
<td>12.5</td>
</tr>
<tr>
<td>Roque</td>
<td>1.6</td>
<td>13.6</td>
<td>2.7</td>
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<tr>
<td>Other sub-Fasnia</td>
<td>–</td>
<td>~30</td>
<td>~10</td>
</tr>
<tr>
<td>Total DHF</td>
<td>32</td>
<td>210</td>
<td>70</td>
</tr>
</tbody>
</table>

Sources: a — Martí et al. (1994)
b — Alonso (1989)
c — B. Booth and G.P.L. Walker (unpubl. data)
d — Walker (1981)
e — Wolff (1985, Tajao ignimbrite only).

$^a$ Estimates of previous studies, for both tephra and dense rock equivalent (DRE) where available.
$^b$ Unnamed plinian deposits of the Cruz sequence, based on the assumption of ten members with 2.5 km$^3$ each.
$^c$ Estimate based on limited thickness data (no well constrained isopachs).
$^d$ Quoted simply as “Unit N”, which may correspond to either the Socorro Member or the Batista Member or both.
Fig. 3. Correlation diagram for the Diego Hernandez Formation showing the stratigraphic relationships between 16 representative sections scattered around the island (inset). The horizontal line represents the contact between the widespread Fasnia and Poris Members. Unlabelled members are deposits which have not been named (such as the many unnamed members of the Cruz Sequence in Sections 10, 11 and 14). Member symbols: Ab — Abrigo, Ad — Aldea, Af — Arafo, Bj — Benijos, Bt — Batista, Ct — Caleta, Cz — Cabezon, DHFbs(i–vii) — see text, Es — Espigon, Fs — Fasnia, Fz — Fortaleza, Hg — Hidalga, Ps — Poris, Rq — Roque, Sc — Socorro, Tc — Taco, Tr — Tarasca, Ts — Tosca.
paper are $2\sigma$, and $^{40}\text{Ar}/^{39}\text{Ar}$ ages from other studies are recalculated based on intercalibrations between fluence monitors (Renne et al., 1998) so that ages are directly comparable to our results where possible). Brown et al. (2003) dated the Fasnia, Poris, Caleta and Abrigo Members using $^{40}\text{Ar}/^{39}\text{Ar}$.

New $^{40}\text{Ar}/^{39}\text{Ar}$ dates for DHF units are reported in Table 1 and discussed below. Laser fusion of individual crystals was employed in order to identify and reject xenocrysts. The ages of several crystals from a single sample are then combined to yield a mean age, and are also plotted on inverse isochron diagrams (procedures of York, 1969; Wendt and Carl, 1991). Weighted mean ages are calculated by weighting the inverse of the variance, after rejecting individual crystals that yield ages outside two standard deviations of the mean (Table 1).

Fig. 4. Composite stratigraphic sections of major members of the DHF. Note the stratigraphic complexity of many members, particularly the Aldea, Fasnia and Poris Members. An approximate scale bar is given in the legend at bottom right but the complex members are not strictly to scale (for example, the thicknesses of many units in the Fasnia section are underrepresented). [Poris section modified from Edgar et al. (2002); Abrigo section modified from Pittari et al. (2006)].
The valid isochrons obtained are within uncertainty of, or very close to, weighted mean ages. A potential problem with weighted mean ages is that xenocrysts only slightly older than the eruption age may be included in, and may skew, the age (Gansecki et al., 1996). Xenocrysts become more abundant upwards in the DHF, indicating that recycling of earlier magmatic components became more significant with time.

In addition, titanite separates from the Roque, Fasnia, Poris and Abrigo Members were dated using (U–Th)/He (Table 1). This method has not yet been widely applied to young volcanic rocks, but has considerable potential (Min et al., 2006), not least because, in contrast to Ar, He retention times in minerals at magmatic temperatures are effectively zero and xenocrystic contamination should therefore not be a problem. Titanite has a (U–Th)/He closure temperature of about 200 °C (Reiners and Farley, 1999), strongly partitions U and Th from melt, and is ubiquitous among the DHF phonolites.

For both dating techniques, full details of analytical procedures may be obtained by application to the authors.

The Roque Member yielded a weighted mean 40Ar/39Ar age of 347±8 ka, indistinguishable from the isochron age of 351±10 ka (Table 1). Two titanite separates from the same sample yielded an average age of 324±23 ka, within uncertainty of the 40Ar/39Ar date. The weighted mean 40Ar/39Ar age of the Roque Member is taken as the preferred age.

Mitjavila (1990) reported a K/Ar date of 266±34 ka for the Tajao ignimbrite unit of the Aldea Member (his Unit II-2, Fig. 2). We obtained indistinguishable 40Ar/39Ar weighted mean ages of two samples from the Aldea Member. One sample also yielded a statistically valid isochron, just outside of 2σ analytical error of the weighted mean age. The mean of the two weighted mean ages is taken as the preferred age of 319±5 ka (Table 1).

Mitjavila (1990) K/Ar dated the Fasnia Member (his unit III-1) at 377±32 ka, inconsistent with his result for the Aldea. We obtained two overlapping 40Ar/39Ar ages for the Fasnia Member, for which the preferred age is again taken as the mean of the two weighted mean ages, i.e. 309±6 ka (Table 1). A (U–Th)/He age of 335±27 ka from a single titanite separate is within uncertainty of the preferred age. The close similarity in measured ages of the Aldea and Fasnia Members is consistent with the generally poor development of the weathering profile separating the two members in the Bandas del Sur. Brown et al. (2003) report a 40Ar/39Ar age of 292±12 ka (recalculated) for the Fasnia Member, slightly younger than, but overlapping the 2σ uncertainty of, our results.

Mitjavila (1990, his Unit IV-2, Fig. 2) and Bryan et al. (1998) dated the Poris Member by K/Ar at 225±52 ka and 316±20 ka respectively. We obtained 40Ar/39Ar ages from two samples of the Poris Member that are barely consistent (Table 1), most likely due to the presence of partly reset xenocrysts with closely similar ages to the eruption age. Because the effect of xenocrysts should be to increase the apparent age of a sample, the younger of the two weighted mean ages is preferred here, and the age of the Poris Member is therefore taken as 268±8 ka (note that the statistically indistinguishable 277 ka average of the two weighted mean ages was reported as the age of the Poris Member by Edgar et al., 2002). Brown et al. (2003) report a 40Ar/39Ar age of 276±10 ka age (recalculated) for the Poris Member, indistinguishable from our results. (U–Th)/He ages were determined on five titanite separates from three different Poris pumice samples. One of these fell outside 2σ error and was rejected. The average of the remaining four is 263±18 ka, within error of the preferred 40Ar/39Ar age.

The Batista sample yields a 40Ar/39Ar weighted mean age of 234±7 ka, indistinguishable from the isochron age of 224±10 ka. Brown et al. (2003) dated the Caleta Member, which underlies the Batista, at 223±10 ka (recalculated), indistinguishable from our result for the Batista Member.

The two Abrigo samples contained the highest proportion of xenocrysts, all “older” than the eruption age, that were rejected from the weighted means (Table 1). The two weighted mean ages are indistinguishable and the mean of 196±6 ka is hence taken as the age of the Abrigo Member. This value is within uncertainty of the 40Ar/39Ar step-heating plateau age of 183±8 ka reported by Mitjavila and Villa (1993). A single (U–Th)/He age is within uncertainty at 194±16 ka. Brown et al. (2003) report a 40Ar/39Ar age of 171±2 ka (recalculated) for the Abrigo Member, which is inconsistent with our results. The discrepancy is most likely related to the presence of partly degassed xenocrysts, which may vary in abundance from sample to sample.

The ages reported here are internally stratigraphically consistent (Table 1), and generally agree with prior 40Ar/39Ar results of Mitjavila and Villa (1993) and Brown et al. (2003), whereas the earlier K/Ar results are frequently inconsistent and show widely varying results for the same unit. The congruence between our ages and those of Brown et al. (2003) represents a significant step towards a precise, rigorous geochronology for the DHF,
although minor discrepancies remain, most significantly for the Abrigo Member. The agreement of the (U–Th)/He ages with the preferred ⁴⁰Ar/³⁹Ar ages (Table 1) is encouraging, and indicates that this technique has great potential for dating Quaternary felsic volcanic suites that contain U,Th-rich phases and where excess ⁴⁰Ar or feldspar xenocrysts are potential problems.

5. Eruption volumes

The lack of an accessible distal record hampers plinian fall deposit volume calculations on oceanic islands. The method of Pyle (1989), which assumes a constant exponential thinning rate with distance from source, was applied to onshore isopachs of DHF fall deposits (Fig. 5). The resulting tephra volume estimates (Table 2) are high, e.g. Aldea: 25 km³, Arafo: 15 km³, Caleta: 15 km³ of tephra. It is possible that significant variations in wind direction and strength during the course of some eruptions distorted the geometry of the isopachs to produce an artificially low thinning rate. This effect was minimized where possible by separately treating each fall unit within a member.

Fig. 5. Isopach and distribution maps for major members of the DHF. (a) Roque Member (thickness in cm); (b) Aldea Member, showing the isopach pattern (thickness in cm) and dispersal axis of the main plinian fall unit, Unit A (the Unit C dispersal axis appears to trend southeast through Tajao); inferred PDC flow paths are shaded; (c) various sub-Fasnia members, showing the lack of overlap between the known outcrops of these members, which has prevented an understanding of stratigraphic relationships based on mapping alone; (d) Fasnia Member (thickness in cm), showing the very significant cumulative thickness of Units A, B, D, F, H, J, L and N; nearby outcrops which reveal different levels of the stratigraphy are joined by line segments and the combined thickness is shown; (e) Portis Member (thickness in cm), only the main plinian deposit, Unit B, is shown [from Edgar et al., 2002]; (f) Arafo Member, combined thickness (in cm) of Units A and D; * Unit A only (overlain by surge deposit), ** Unit A + Unit D (intervening surge deposit present); (g) Arafo Member surge deposit, Units B and C (thickness in cm); (h) Caleta Member, Unit A (thickness in cm), showing an overall fall dispersal pattern modified by intermittent surge activity; (i) Caleta Member, Unit B (thickness in cm); (j) Caleta ignimbrite (thickness in m), showing the extensive outcrop on the southeastern slopes and more limited exposure in the caldera wall, in the north near Los Realejos and on the west coast (inset); (k) Batista and Socorro Members (thickness in cm); Batista data are given as Unit A/Unit B; * lithic-rich pipes in the Socorro Member; (l) Abrigo ignimbrite (thickness in m), showing the highly extensive present-day outcrop. Note: in many maps, some data have been omitted for the sake of clarity.
were also found using the approach of Carey et al. (1995). Consequently, maximum fall deposit volumes (Table 2) were also found using the approach of Carey et al. (1995).

Maximum volume estimates for ignimbrites were obtained by extrapolation from the volume of preserved onshore deposits. The proportion of ignimbrite deposited offshore was estimated by consideration of dispersal patterns, observed onshore thickness and facies variations, and offshore drillhole data (Schmincke and Sumita, 1998). Possible intracaldera fill was ignored because the subsurface geology of the Las Cañadas Caldera is still poorly understood. The maximum volumes obtained (Table 2) are very high and are regarded as order-of-magnitude estimates only. It seems likely, however, that the major DHF eruptions each produced $5-30 \text{ km}^3$ of tephra ($1-10 \text{ km}^3$ dense rock equivalent, DRE) and are therefore comparable to other well-studied large plinian eruptions, such as Pinatubo (1991, $\sim 4 \text{ km}^3$) and Katmai (1912, $\sim 3.5 \text{ km}^3$). The total volume of the DHF cycle is estimated to be $70 \text{ km}^3$ of magma (DRE), and the phonolite output rate during DHF I–DHF III time was therefore approximately $0.5 \text{ km}^3/\text{k.y.}$. This is one to two orders of magnitude less than the long-term output rate of the Hawaiian and other hotspot tracks.

In addition to problems noted above, accurate estimation of deposit volumes on Tenerife is undermined by difficulties arising from highly complex PDC deposit geometries, poor preservation within 10 km of vent, burial and caldera collapse. The current study represents the most complete mapping of individual DHF units undertaken to date, and the volume estimates in Table 2 are therefore the most reliable available at the present time. Improved volume estimates will be possible in the future if detailed correlation with offshore ash layers (Schmincke and Sumita, 1998) can be achieved.

6. Descriptions of individual members of the DHF

In the Bandas del Sur, the base of the DHF is often a prominent disconformity with an associated thick soil, cut into Guajara Formation and older units. The disconformity represents approximately 300,000 years of non-deposition (apart from the eruption of flank basalts). In the caldera wall, the DHF laps onto the steeply dipping head of the Orotava valley landslip scar (Martí et al., 1994), although some members, especially the Abrigo, occur more widely at the top of the Las Cañadas caldera wall scarp.

Summary descriptions of each of the named members are provided here, grouped into the informal DHF subdivisions already outlined. The DHF basal sequence is poorly exposed except at the base of the DH wall. The Aldea, Fasnia, Poris, Arafo, Caleta and Abrigo Members are of regional extent and occur widely across the Bandas del Sur, in the DH wall, and in some cases in northern and western Tenerife. The Cruz sequence of up to 15 plinian deposits likewise extends over much of the island, but only 4 deposits are sufficiently distinctive to have been named and correlated. Other named members in the lower DHF are only locally exposed and their precise stratigraphic relationships remain uncertain. Un-named units (typically only seen at one location) are mentioned at their appropriate stratigraphic position.

Following Wolff et al. (2000) we use the concentration of Zr, a strongly incompatible element, as an indicator of magmatic evolution in the phonolitic pumices, and Nb–Zr relations to identify chemostratigraphic divisions and phonolite types. Quoted volumes are estimates of erupted magma (DRE), calculated as described above. Lithic and pumice contents were averaged from visual estimates of a large number of outcrops.

6.1. Fortaleza Member

The Fortaleza Member is exposed in the northern sector of the Las Cañadas caldera wall (La Fortaleza), 5 km NW of the DH wall (Fig. 1). It is assigned to the DHF on the basis of a 370 ka K/Ar age determination (Ancochea et al., 1990), which places it below the Roque Member. No equivalent has been identified in the DH wall. It forms a shear 50-m scarp between mafic Lower Group rocks and the Santo ignimbrite of the Fasnia Member. The Fortaleza Member (Fig. 3, Section 16) is divided into five units (from base to top): A (55 cm), a pale non-welded ignimbrite; B (35 cm), a reverse-graded, incipiently welded, lithic-poor (5%) plinian fall deposit with prominent flow-banded obsidian clasts; C (5 cm), a fine ash bed with sharp but irregular contacts, of probable surge origin; D (2.6 m), a green-grey plinian fall deposit with a moderately welded lower half and a densely welded upper half, grading up into E (50 m), a clastogenic lava with a green-grey devitrified groundmass with zones of obsidian, pervasive columnar jointing and flow banding, flow folding and ramp structures. This sequence of facies reflects an evolution in eruption style from a high plinian column to fire-fountaining and spatter agglutination. Similar sequences are common in the proximal Guajara and Ucanca formations (Zafirlla, 2001; Soriano et al., 2002) but are not exposed elsewhere in the DHF.

The Fortaleza Member is weakly porphyritic (<5%), chemically similar to the Guajara Formation and varies slightly in composition (Fig. 6), with the most evolved compositions occurring in Unit B, and the least evolved above the densely welded upper half of Unit D (see also Zafirlla, 2001).
6.2. Diego Hernandez Formation basal sequence (DHFbs)

The lower 50 m of the exposed DH wall consists of a succession of fluvial sedimentary deposits with palaeosols, interbedded scoria and lavas of the Dorsal rift system, and primary and reworked phonolitic pumice deposits (Fig. 3, Section 13). The sediments signify that early infilling of the head region of the La Orotava valley was dominated by fluvial processes, with sediment sourced from the surrounding landslide scarps and ongoing volcanism. DHFbs exposures are very limited outside the DH wall, and few units have been formally named. Except where noted, DHFbs pumice deposits have high Nb/Zr geochemistry, similar to the underlying Guajara Formation (Fig. 6).

6.2.1. Lower sedimentary interval (DHFbs)

The oldest phonolitic units in the DHF type section are two thin primary fallout units, informally designated DHFbs(i) and DHFbs(ii), in a sediment package that underlies a prominent scoria cone and DH97-18 basaltic lavas of Wolff et al. (2000) in the DH wall. Reworked pumice of similar composition occurs in a 13-m-thick sequence of pumice-rich gravels above the basalt and probably represents the products of at least one later eruption of similar magma. This sequence is capped by a 1.8-m lithic-rich ignimbrite, DHFbs(iii), and the DH97-19 and -20 lavas of Wolff et al. (2000).

6.2.2. Espigon member (DHFbs)

The Espigon Member is not seen in the DH wall but occurs 7 km to the east, on the upper slopes of the volcano (Fig. 3, Section 11; Fig. 5c), where it underlies two DHFbs plinian fall deposits, the upper of which is tentatively correlated with DHFbs(iii). It comprises five units: A (4 cm), a basal ash bed; B (35 cm), a white, normally graded plinian fall deposit; C (25 cm), a dark grey, stratified mafic plinian fall deposit; D (25 cm), interbedded fine ash and lithic fall layers; E (>1 m), a fine-grained, massive valley-ponded ignimbrite. The fine ash and lithic beds probably record phreatomagmatic activity. The Espigon phonolitic component is very noteworthy for its low-Nb, low-Zr composition, similar to the Arafo and Caleta Members of DHF II (Fig. 6), while the mafic pumice is tephriphonolitic.

6.2.3. Ignimbrites and gravels (DHFbs)

The lavas at the top of the lower sedimentary interval in the DH wall are overlain by a 3-m sequence of interbedded primary and reworked ignimbrite and minor pumice-rich gravels, DHFbs(iv). The uppermost unit is a primary ignimbrite containing occasional mingled-magma banded pumices with a phonotephritic mafic component. It is interpreted as the product of a single eruption which included pauses of sufficient duration for minor reworking. The top of DHFbs(iv) is oxidized and weathered, and is overlain by boulder-bearing gravel.

Three other minor (≤50 cm) and partially reworked ignimbrites, DHFbs(v)–(vii), occur within the 4.5 m of sediment that separate DHFbs(iv) from the Roque Member.

6.2.4. Roque Member (DHFbs)

With a southerly dispersal (Fig. 5a), the Roque Member (347±8 ka, 3 km³) consists of a massive, pale grey, plinian fall deposit up to 2.6 m thick, with prominent brown-stained lithics and minor banded pumice. No PDC deposits have been correlated with this member, suggesting a relatively simple, sustained plinian outburst. In the Bandas del Sur, the Roque Member corresponds to the lower of the two “Aldea Blanca pumice fall deposits” of Brown et al. (2003); it also occurs in the DH wall (Fig. 5a). It is chemically distinct from all other analyzed DHFbs units, with a similar trace element composition to the Aldea and Fasnia Members (Fig. 6).

6.2.5. Upper sedimentary interval (DHFbs)

In the DH wall, the Roque Member is overlain by 15 m of coarse fluvial gravels with occasional boulders and
several soil horizons. Among the gravels are at least four very pumice-rich beds that probably represent the products of distinct eruptions. The interval is capped by the Tajao ignimbrite of the Aldea Member.

In summary, the DHFbs contains minor pumice deposits that record at least 7 explosive eruptions of phonolitic magma. These deposits are dwarfed by the products of later major DHF eruptions. In several cases, deposit thickness is similar to that of the 2-ka Montaña Blanca sub-plinian fallout in this area (Ablay et al., 1995). We suggest that the phonolitic volcanism recorded in the DHFbs is comparable in magnitude to Holocene phonolitic activity of the Teide–Pico Viejo complex.

6.3. Aldea Member (DHF I)

The Aldea Member (319±5 ka, 3 km$^3$) is widely exposed on the southern slopes as a thick (3.5 m), highly stratified plinian fall (and minor surge) sequence beneath the Fasnia Member (Fig. 5b). This sequence corresponds to, but is far more complex than, the upper of the two “Aldea Blanca pumice fall deposits” described by Brown et al. (2003). It correlates with a complex ignimbrite sequence (including the Tajao ignimbrite of Wolff (1985)) exposed in the Tajao area near the SE coast and also in the DH wall (Fig. 3, Sections 5–8 and 13). The lowest fall unit, A (106 cm) is divided into five subunits on the basis of lithic content (5–40%) and grainsize (Fig. 4a); banded pumice appears in the upper part of Subunit A3 and continues to the top of the unit. Unit B is a thin (4 cm) white ash bed, interpreted as the co-ignimbrite ash cloud deposit of the Tajao ignimbrite, a PDC deposit restricted to the DH wall (12 m) and the Tajao area on the SE coast (8.6 m). The ignimbrite is rich in coarse (>50 cm) banded pumice and red-brown hydrothermally altered lithic fragments, like its bounding fall deposits, but is internally complex with rapid lateral facies variations. It is overlain by Unit C (74 cm), a stratified fall/surge deposit divided into four subunits including a prominent lithic-rich surge deposit, Subunit C2 (Fig. 4a); banded pumice occurs in Subunit C1 but is otherwise absent. The Unit C plinian fall has a more easterly dispersal than Unit A and is exposed within both the ignimbrite sequence and the fall sequence as a useful marker horizon. Unit D is a thin white ash bed related to the Antagas ignimbrite (6 m), another laterally complex pumice-rich ignimbrite which overlies Unit C in the Tajao area and has an erosional contact with the Tajao ignimbrite in the DH wall. It has multiple coarse pumice concentrations and finer-grained lithic-rich horizons, with minor banded pumice, perhaps erosionally recycled from the Tajao ignimbrite. Unit E (5 cm) is a thin plinian fall deposit overlying Unit D and the Antagas ignimbrite. Unit F (10 cm proximally, 1 cm distally) is another fine white ash bed, the ash cloud deposit of the Guama ignimbrite (5 m), which overlies Unit E in the Tajao area and the Antagas ignimbrite in the DH wall. It resembles the Antagas and has an upper pumice concentration zone with a small proportion of grey-and-white banded pumice. Unit G (50 cm) is a fine-grained and relatively lithic-rich plinian fall deposit, overlain by Unit H (3 cm), a thin fine-grained and ashy horizon which may correlate with a fourth PDC deposit. The Infantes ignimbrite (25 m) is highly complex, displaying strong lateral facies variations and stacking of pumice concentration zones and coarse lithic breccias, alternating with fine-grained stratified facies, without clear flow unit boundaries. Pumice clasts, some highly porphyritic (40%), reach 30 cm in diameter and lithics 50 cm, with a diverse range of lithic types including syenites and hydrothermally altered rocks. Banded pumice occurs at various levels in the deposit. On the southern slopes, the Unit H ash bed is overlain by Unit I (85 cm), a plinian fall deposit which is similar in grainsize and lithic content to Unit G. At one locality near the town of La Maretta (Fig. 5b), Unit I is conformably overlain by a thin grey ash bed, Unit J (2 cm), followed by a thick planar-stratified surge deposit, Unit K (2 m), which may correlate with the Infantes or a possible fifth ignimbrite seen at one location in the complex DH wall sequence.

The Aldea eruption began with a high intensity plinian phase marked by several changes in column height and vent stability, followed by repeated partial collapse to form pyroclastic flows which exploited a drainage notch in the Guajara-age caldera wall to descend the deep Barranco del Rio and reach the sea near Tajao (Fig. 5b). Fines depletion of the Tajao ignimbrite is attributed to ingestion of air under turbulent flow conditions during the descent of the steep slopes of the Las Cañadas edifice. Complex upsequence facies variations, including concentrations of dense lithics at various stratigraphic heights, indicate that, at least in most cases, the Aldea ignimbrites progressively aggraded from sustained pyroclastic density currents (Brannley and Kokelaar, 2002).

Aldea Member phonolitic pumices have chemical compositions characterized by relatively low abundances of Nb at a given Zr content (Fig. 6), which is the signature of the DHF I chemostratigraphic interval (Wolff et al., 2000). Bulk compositions of pumices vary widely due to the presence of tephriphonolitic and basanitic components (Wolff, 1985), but the phonolitic component is itself highly variable (Fig. 6) and shows overall compositional zoning.
6.4. Cabezon Member

The Cabezon Member has only been recognized on the Dorsal Ridge (Fig. 3, Section 14), where it underlies a distinctive scoria flow deposit that in the DH wall lies between the Aldea and Fasnia Members. Twenty-three distinct horizons, grouped into 12 units (Fig. 4b), consist mainly of stratified plinian fall deposits of variable lithic content (5–90%) and pumice attenuated by diagenetic compaction (Branney and Sparks, 1990). Internal disconformities and wedge geometries indicate periods of surface erosion or surge transport and erosion. The dramatic fluctuations in lithic content indicate highly unstable vent dynamics, which must have influenced the stability and height of the eruption column.

6.5. Other sub-Fasnia members

The following six DHF deposits are all sufficiently distinctive and/or exposed over a wide enough area to warrant formal names, and are all older than the Fasnia Member, but are otherwise of uncertain stratigraphic position.

6.5.1. Tarasca Member

This poorly exposed block and ash flow deposit up to 3 m thick forms the lowest known member of the DHF in the La Orotava valley (Fig. 3, Section 15; Fig. 5c). It is a massive, clast-supported deposit with dense blocks of crystal-rich phonolite up to 75 cm in diameter. It is inferred to have been produced by gravitational collapse of a lava dome in the NE sector of the Las Cañadas Caldera.

6.5.2. Guirres Member

The Guirres Member is a >1-m-thick, lithic-poor (5%) plinian fall deposit exposed beneath the Fasnia Member at several localities in the southern Guimar valley (Fig. 5c).

6.5.3. Tosca Member

Ponded against the northern slopes of the Montaña Guaza lava dome complex in SW Tenerife (Fig. 3, Section 4; Fig. 5c), the Tosca ignimbrite (Huertas et al., 2002) lies in erosive contact (but no apparent palaeosol) on the following deposits: Unit A (2.4 m), a complex succession of phreatomagmatic white-grey, massive to laminated ash beds (<10 cm thick) with sharp planar contacts, variable accretionary lapilli content and abundant monomictic, angular lava clasts in the upper beds, and an alternation of plinian fall deposits (Units B, D, F and H; 20–90 cm each; with grainsize increasing and lithic content decreasing from base to top) and thin white ash beds (Units C, E and G; 1–3 cm each; laterally continuous). The ignimbrite (>5 m) is white, massive and rich in aphyric tube pumice (60%, <2 cm) and is overlain by an unidentified plinian fall deposit, followed by the Abrigo ignimbrite. The early hydromagmatic phase of the eruption was succeeded by steady growth of a high eruption column, periodically interrupted by either temporary vent blockage, partial column collapse or brief phreatomagmatic episodes. As the vent continued to widen, the eruption intensity may have become so great as to overload the eruption column, resulting in gravitational collapse of the column and the production of pumiceous pyroclastic flows which flowed down the southern flank of the edifice and deposited the Tosca ignimbrite.

6.5.4. Tarta Member

The Tarta Member is noteworthy for its prominent exposure at one very accessible cutting on the main Dorsal Ridge road (Fig. 5c), where it forms a white phonolitic unit sandwiched between two thick black scoria deposits. It consists of five units: A (8 cm), a thin basal coarse plinian deposit with grey-and-white banded pumice and outsized pumice clasts to 16 cm; B (15 cm), a planar-laminated ash-lapilli surge deposit; C (110 cm), a diffusely stratified plinian fallout with a normally graded basal layer and a more lithic-rich (10–50%) lower third with prominent red-brown altered lithics; D (1.5 cm), a cream ash bed; and E (50 cm), a coarse, reverse-graded plinian deposit, which is overlain by 1 m of variably rounded reworked pumice and lithic fragments. The Tarta pumice is chemically very similar to the Aldea Member (Fig. 6) and could conceivably correlate with it; however this is unlikely because it occurs at locations almost diametrically opposite the dispersal direction of the Aldea fallout beds.

6.5.5. Taco Member

The Taco Member is a complex plinian succession preserved in NW Tenerife (Fig. 3, Sections 2 and 3; Fig. 5c) and apparently pre-dating the Fasnia Member. It consists of six units (Fig. 4c): A (75 cm), a white, poorly sorted plinian fall deposit with angular/platy pumice; B (90 cm), a plinian deposit stratified by grainsize and lithic content and zoned from white at the base to medium grey at the top; C (50 cm), a sequence of light grey, medium grey and white fine ash beds, some rich in accretionary lapilli, and a minor plinian fall bed; D (70 cm), a diffusely stratified plinian fall deposit composed of medium grey and dark grey pumice as well as banded pumice containing both of these components; E (25 cm), a sequence of fine-grained plinian fall deposits (light grey to black, normal to reverse graded) and a dark...
grey ash bed; F (45 cm), a well stratified, poorly sorted plinian deposit with variably rounded pumice (alternating light and medium grey). This well-stratified sequence suggests a highly unstable, pulsatory eruption column with intermittent phreatomagmatic activity. The Taco Member is compositionally zoned vertically from white to grey phonolite; it chemically resembles the DHFbs units, suggesting that it may pre-date the Aldea Member.

6.6. Fasnia Member (DHF I)

The Fasnia Member (309±6 ka, 13 km$^3$) consists of 21 recognized units, including a basal phreatomagmatic ash and 7 ignimbrites, grouped into a lower and an upper sequence on the basis of a widespread minor disconformity (Fig. 4d) that records a very brief pause in eruption. It represents one of the largest and most complex eruptions in the history of Tenerife. It is the subject of a separate paper (Edgar et al., in preparation) and will only be briefly described here.

Both sequences consist of complex intercalations of thick, widespread plinian fall deposits (Fig. 5d), lithic-rich surge deposits and ignimbrites. A basal accretionary lapilli-rich phreatomagmatic ash, wet enough to drape vegetation and undergo soft-sediment deformation, records an opening phase of magma–water interaction. Caldera collapse is inferred to have occurred during the Fasnia eruption in a gradual or piecemeal fashion, recorded by extensive lithic breccia facies in several of the ignimbrites. A proximal welded ignimbrite facies in one unit (Santo) represents the only welded ignimbrite in the DHF.

The Fasnia Member exhibits overall compositional zoning, albeit with much scatter, attributed to mixing between different reservoirs of phonolitic magma, similar to the Poris Member (Edgar et al., 2002 and below). As in the Aldea Member, intermediate and mafic magmatic components occur through most of the Fasnia Member, but are most abundant among early-erupted beds.

6.7. Maja Member (DHF I)

The Maja Member occurs beneath the Poris Member in a restricted area in the northern section of the DH wall. It is probably (but not conclusively) younger than the Fasnia Member and consists of 6 units: A (>41 cm), a white, poorly sorted plinian fall deposit with a lithic rich upper 15 cm; B (67 cm), a complex ignimbrite and surge sequence; C (51 cm), a white wet ash deposit with abundant accretionary lapilli, and flame structures at the upper contact; D (38 cm), a surge deposit with shallow cross-beds; E (220 cm), a lithic rich (∼50%) ignimbrite with a basal surge bed; and F (200 cm), a coarse, lithic-rich, plinian fall deposit, with an eroded and channelled upper contact overlain by sediment. The Maja Member is noteworthy for being chemically unique among DHF units, with Nb–Zr relations intermediate between DHF I and DHF III (Fig. 6), although its physical character is similar to other DHF I and II deposits.

6.8. Poris Member (DHF I)

The Poris Member (268±8 ka, 3.5 km$^3$) is another complex and widespread plinian and ignimbrite succession which is separated from the Fasnia Member in the DH wall by a thick sequence of basaltic lavas. It has been described in detail by Edgar et al. (2002) and Brown and Branney (2004a).

6.9. Arafo Member (DHF II)

The DHF II chemostratigraphic subdivision is characterised by very low Nb/Zr compared to other DHF units (Fig. 6). The Arafo Member (4 km$^3$) is presumed equivalent to the Sabinita Formation of Brown et al. (2003). However, the type section of Brown et al. (2003) lies outside the main distribution of the deposit, which is well exposed at many locations in the Guimar valley around the town of Arafo (Fig. 5f), after which it is named. It consists of a thick (up to 4 m), white, massive, lithic-poor (<1%) plinian fall deposit (Fig. 4f) with poorly sorted, highly angular near-aphyric blocky or platy pumice with occasional banded pumices. In northern Tenerife it displays a finer-grained, more lithic-rich (20%) base (Subunit A1, 30 cm maximum), and a 1–2-mm fine ash is seen at the base in proximal exposures. Proximally and on the eastern slopes (Figs. 5g, 7a), it is divided into two units (A and D) by an intra-plinian surge deposit, consisting of discontinuous pinkish-grey and white coarse ash beds (Unit B, up to 35 cm) overlain by a lapilli-surge
deposit (Unit C, up to 1.5 m) with planar and cross-stratification defined by both grainsize and pumice:lithic ratio. Most pumice is sub-rounded but horizons of coarser and more angular pumice indicate simultaneous plinian fallout. This becomes increasingly dominant with height as Unit C grades into the upper plinian fallout, Unit D, which resembles Unit A but exhibits an upward increase in lithic content. The poor sorting of the fall deposit was probably enhanced by the weakness of the dispersing winds, which appear to have changed direction from southerly to westerly during the eruption. The very low lithic content and lack of grainsize grading and stratification in Unit A indicates a stable conduit and vent. However the intra-plinian surge deposit records a likely phreatomagmatic episode. The surge travelled >15 km to the east coast, depositing a basal head deposit (Unit B) and a well-stratified, valley-filling body deposit (Unit C).

The phonolitic component is chemically homogeneous, except for the upper part of Unit D which is considerably less evolved. The mafic component, of tephriphonolite composition, occurs as black bands and streaks in mingled pumice throughout the deposit. In the DH wall, western Dorsal Ridge, and Guimar valley, the Arafo Member is overlain by basanitic scoria fall deposits.

6.10. Minor DHF II units

Two unnamed, well-sorted, lithic-poor coarse phonolitic fall deposits (25 and 55 cm thick), chemically similar to the two main DHF II members, lie above reworked and weathered material that caps post-Arafo scoria in the DH wall and western Dorsal Ridge (Fig. 1). They are overlain by a scoria bed and a thin (21 cm) PDC deposit, separated from the Caleta Member by a palaeosol and at least one further scoria fall deposits.

6.11. Caleta Member (DHF II)

The Caleta Member (3.5 km³) records another complex eruption marked by alternating phreatomagmatic and magmatic episodes and the generation of a highly variable ignimbrite sequence. It consists of five units (Fig. 4g) and is equivalent to the 223 ±10 ka Caleta Formation of Brown et al. (2003). Unit A (up to 42 cm) is a complex sequence of fine white ash beds, some rich in accretionary lapilli, and variously lithic-rich pumice deposits with fine lapilli- to coarse ash-sized clasts. Of 14 identified subunits, the most widespread and distinctive is a laminated white ash bed. The thickness variations of this unit generally conform to plinian-style fallout from a vent within the LCC, but the isopach map also shows irregular maxima (Fig. 5h). On the outcrop scale (Fig. 7b), the deposit mantles topography but displays irregular undulations which earned it the name “the Wavy Deposit” from previous workers (Alonso, 1989; Bryan et al., 1998). We attribute the waviness to a variety of mechanisms, including: (1) a localized surge component in some beds, indicated by clear pinch-and-swell stratification and gradual thickness variations; (2) draping of small boulders and shrubs; (3) impact sags formed by large pumice clasts of Unit B being deposited on wet ash beds; and (4) post-depositional slumping of wet ash on local steep slopes resulting in irregular folding, waviness, and small-scale faulting. Unit A was generated by a series of phreatomagmatic explosions sourcing a high plinian-style column dispersed to the SE by winds and accompanied by the generation of pyroclastic surges.

Unit A is overlain by Unit B, a thick (2.6 m), white plinian fall deposit with a focused dispersal to the SE (Fig. 5i) and characterized by very coarse grainsize (pumice up to 40 cm, lithics up to 20 cm), strong reverse grading, diffuse grainsize stratification, variable lithic content (2–15%) and prominent tube pumice. Subunit B1 is a finer-grained, stratified and more lithic-rich (up to 30%) basal horizon. B2 is the main coarse plinian deposit, which is capped by B3, a thin (8 cm) but complex sequence of very lithic-rich (70–100%) fall layers and fine ash laminae (2 mm thick). This is conformably overlain by Unit C, a discontinuous sequence of up to six beds (5–30 cm each), including a lower white accretionary lapilli ash fall bed (Subunit C1), a very extensive grey ash bed (Subunit C2) with pumice and lithic lapilli and surge characteristics (irregular thickness variations, erosive base, rare cross-lamination, rounded pumice), overlain by a variable number of other ash beds and plinian fall horizons.

The Caleta ignimbrite (Unit D) generally overlies Unit C (Fig. 7b) but there is some intercalation of the two, and some of the Unit C ash beds may have a co-ignimbrite origin. In the Bandas del Sur, the ignimbrite is thickest (>12 m) and most complex around the town of Tajao (Fig. 5j) but thinner veneer-like deposits are widespread. A discontinuous lithic-rich ground surge deposit occurs at the base of the ignimbrite at one locality near Tajao. Three distinct subunits have been identified in the body deposit (Fig. 4g): Subunit D1, a discontinuous, fine-grained and pervasively altered phreatomagmatic deposit; Subunit D2, a pumiceous ignimbrite with a lower coarse pumice concentration zone; and Subunit D3, the thickest subdivision, with a more lithic-rich composition (10–40%), massive to stratified texture and a coarse (≤ 30 cm) lithic breccia near the top. The latter contains diverse lithologies, including syenite, and may record an episode of large-scale vent collapse or small-scale caldera collapse. The Caleta ignimbrite displays
complex facies variations, with lithic breccias and pumice concentration zones occurring at variable heights in the deposit. A complex non-indurated, fines-depleted, stratified facies has been identified in the La Orotava valley. Where the ignimbrite is absent (Guimar valley), Unit C is overlain by Unit E (up to 80 cm), a massive plinian fall deposit with 5–10% lithics and minor mingled and mafic pumice which become more abundant upward.

The dominant phonolitic magmatic component of the Caleta is essentially uniform in composition and is similar to the Arafo Member (Fig. 6). Mafic blebs and streaks, often crystal-rich, occur in pumice throughout the member but are most abundant in Unit E. The mafic material contains both basaltic and intermediate components and has the average composition of a tephrite with up to 5% MgO.

6.12. Cruz sequence (DHF III)

Wolff et al. (2000) defined chemostratigraphic division DHF III on the basis of an up-section return to high Nb/Zr phonolite (Fig. 6). Beneath the climactic Abrero ignimbrite, DHF III is dominated by the products of plinian fallout eruptions with a subordinate role for phreatomagmatic and PDC-producing activity. The products of these eruptions form a succession of at least 6 and as many as 15 or more members (separated by weathering and/or palaeosol horizons) occurring between the Caleta and Abrero Members. This succession is named for the locality of Cruz del Roque (Fig. 5k) where at least 6 primary members, including the distinctive basal Batista Member, are seen in a single section. This interval corresponds to the two “pumice fall units” of Brown et al. (2003). Most of these deposits have not been named because field correlation is hampered by their strong similarities, including white phonolitic composition, low crystallinity, moderate grain size, low lithic content (<5%), and lack of distinctive internal features such as ash layers or PDC deposits. Chemical analysis has allowed distinction between some unnamed units. Four larger and more distinctive members have been named (Batista, Socorro, Hidalga and Benijos) and are described below. Overall, the degree of magmatic evolution increases upwards within the Cruz sequence.

6.12.1. Batista Member

The Batista Member (234±7 ka, 2 km³), widely exposed in SE Tenerife (Fig. 5k), consists of two units (Fig. 4h). Unit A is a sequence of interbedded lithic-rich surge deposits and normally graded plinian fall horizons, with a maximum thickness (1 m) and greatest complexity around the town of Poris de Abona. The surge deposits typically have erosive bases, wavy contacts (often asymmetric), thickness variations, high lithic content (up to 80% but <5 mm diameter), rounded pumice and poor sorting. Two particularly prominent wavy lithic-rich beds have been designated Subunits A1 and A3 and are separated by plinian fall deposit A2. Unit B is a thick (2.25 m) reverse graded, lithic-poor (2–5%) plinian fall deposit, with near-aphyric pumice. The eruption progressed from an early phase of pyroclastic surge generation associated with vent instability and/or phreatomagmatism to a later phase of sustained plinian-style activity with steady column growth. The Batista Member is among the least compositionally evolved Cruz sequence units, with ~1100 ppm Zr (Fig. 6) and minor compositional variation but no significant zonation. At least two minor fallout units separate the Batista from the overlying Socorro Member.

6.12.2. Socorro Member

Exposed mainly in the Guimar valley (Fig. 5k), the Socorro Member (1 km³) comprises three units (Fig. 4i): A (10 cm), a thin basal plinian deposit capped by a locally wavy and erosive, discontinuous lithic-rich surge deposit; B (120 cm), a white, lithic-poor (<1%) plinian fall deposit with poorly sorted, platy, angular, near-aphyric pumice containing fine spherical vesicles; and C (100 cm), a poorly preserved surge deposit rich in millimetre-sized lithic fragments (40–80%) and displaying a gradational to sharp, wavy lower contact (wavelength of several metres, amplitude 0.5 m). Unit C is often overlain by thick reworked deposits of similar composition. At several localities in the lower Guimar valley, the Unit B plinian deposit contains swarms of irregular vertical pipe-like features which are distinguished by their abundant fine-grained (<2 mm) lithic fragments (up to 40%). These are interpreted as post-depositional structures formed by water percolating down through the pumice and carrying fine lithics from Unit C through the larger pore spaces of Unit B. This may have occurred due to heavy rains shortly after the eruption, which is consistent with the widespread and thick reworked pumice overlying the member. The Socorro eruption was marked by the generation of lithic-rich surges in the opening and closing stages and an intervening period of plinian activity marked by vent stability, indicated by low lithic content. The Socorro Member has a similar composition to the Batista, but displays a mild vertical chemical zonation.

6.12.3. Hidalga Member

The Hidalga Member immediately overlies the Socorro Member in the Guimar valley (Fig. 3, Section 12). It consists of (Fig. 4j): a basal lithic-rich (40%) bed with
rounded pumice of probable surge origin (Unit A, 10 cm) and a massive lithic-rich (10–20%) plinian fall deposit (Unit B, 130 cm). The Hidalga Member is chemically similar to the Batista and Socorro Members, but pumices occasionally contain small mafic blebs. At least 3 unnamed units overlie the Socorro–Hidalga interval.

6.12.4. Benijos Member

Forming the most distinctive deposit within the Cruz Sequence on the northern slopes, the Benijos Member has been divided into three units (Fig. 4k). Unit A (up to 2 m) is a complex sequence of normally graded plinian fall deposits with intercalated fine pyroclastic surge beds. At the type locality, A is overlain by Unit B (up to 3 m), a highly stratified reworked deposit consisting of alternating pumice and lithic layers. Units A and B are truncated at a high angle and this surface is mantled by a highly stratified, fine-grained, lithic-rich fall deposit (Unit C, >2 m). Units B and C are absent in the DH wall, where Unit A directly underlies a basaltic lava beneath the Abrigo Member. There are no evident palaeosols and the entire sequence can be interpreted as the product of a single eruption. The opening plinian phase was characterized by pulsatory eruption dynamics, probably due to intermittent phreatomagmatic explosions which generated fine ash and pyroclastic surges. A pause in activity, perhaps of up to several months duration, allowed local reworking of the deposits by wind or water, followed by a phase of phreatic explosive activity which produced a highly stratified, lithic-rich fall deposit. In contrast to the lower Cruz sequence units, the Benijos Member exhibits both highly evolved compositions and strong vertical chemical zoning (base = 1680 ppm Zr, top = 1170 ppm Zr).

6.13. Abrigo Member

The Abrigo Member (between 196 and 171 ka, see above, 20 km³) is the youngest and most widespread deposit in the Diego Hernandez Formation (Fig. 3; Fig. 7c) and was erupted during the caldera collapse event that terminated the DHF cycle. Physical features of the Abrigo Member ignimbrite, including depositional characteristics and facies variations, are described in detail by Pittari and Cas (2004) and Pittari et al. (2005, 2006).

The ignimbrite exhibits regional variations in lithic clast lithology and pumice composition radial to Las Cañadas, consistent with eruption from multiple events during caldera collapse (Pittari, 2004; Pittari et al., 2006). It contains the greatest range in magmatic compositions of any DHF unit (Fig. 6), from basalt with 9% MgO to highly evolved phonolite (1800 ppm Zr), and displays the widest range in juvenile clast textures, from near-aphyric pumice to cognate, rheologically solid crystal-rich mafic to felsic juvenile clasts of 60–100% crystallinity (Nichols, 2001). Seemingly, the entire magmatic system was eviscerated during the catastrophic Abrigo eruption.

7. Geochemistry

The general petrology and geochemistry of the DHF has been described by Wolff et al. (2000), while more detailed descriptions of the Aldea and Poris Members are given by Wolff (1985) and Edgar et al. (2002) respectively. Additional features of pumice chemistry in individual DHF members are briefly summarized above. In this section, we focus on the temporal and geochemical evolution of the DHF phonolites in the context of the chronology and erupted volumes of magma, in particular the repeated eruption of phonolitic magma with two distinct trace-element signatures. For representative analyses, see the following in Tables 3–5 of Wolff et al. (2000): DH97-22d, Aldea; DH97-2d, -4a, Poris; DH97-5a, -9b, 96TF-3, Arafo; DH97-9b, Caleta; DH87-14, -15, -16, Benijos; T97-2WR, -3WR, -4WR, Abrigo; and Edgar et al. (2002) for several more analyses of Poris Member pumices.

Major element compositions of phonolites range from metaluminous to weakly peralkaline, with up to 16 wt.% total alkalies. The phenocryst assemblage is sodic sanidine or anorthoclase + clinoipyroxene + magnetite + biotite + titanite + hauyne or sodalite ± nepheline. The least evolved phonolites may additionally have small amounts of kaersutite and ilmenite, while sodalite and nepheline are restricted to the more evolved compositions. There are no significant differences in phenocryst assemblage between DHF I, II and III phonolites, although hauyne is more prominent in DHF I units. Total phenocryst contents vary widely; most pumices have ≤5% phenocrysts, but highly porphyritic pumices occur in the Aldea, Poris and Abrigo Members. Most samples have been at least slightly modified by loss of alkalies and Na/K exchange, but the freshest DHF I pumices have compositions very close to the 1 kbar water-saturated phonolitic minimum in the Ne–Ks–Q system (Hamilton and MacKenzie, 1965), and are mildly peralkaline with (Na+K)/Al ≈ 1.1. Those from DHF III have lower Al₂O₃ ((Na+K)/Al ≈ 1.2) and are slightly less silica undersaturated, although still strongly ne-normative.

Six of the major members (Aldea, Fasnia, Poris, Arafo, Caleta, Abrigo) and some minor units of the DHF additionally bear a mafic magmatic component, which most commonly appears as black streaks and patches in banded pumice. In any one unit, the mafic component
itself typically includes both basaltic and intermediate (tephriphonolite) compositions introduced by pre-eruptive magma mixing (Wolff, 1985; Edgar et al., 2002).

Relations between Zr and Nb contents in the phonolites are highly variable and systematic (Fig. 6; see also Wolff et al., 2000). Most DHFbs phonolites have relatively high Nb/Zr. This chemistry characterizes the earlier Guajara Formation, and at least some of the Ucanca Formation and Lower Group phonolites. DHF I phonolites, in contrast, have lower Nb/Zr over a wide range of Zr contents. DHF II phonolites have very low Nb/Zr and show much less compositional variation. DHF III phonolites mark a return to the high-Nb/Zr, Guajara-like chemistry. Minor units tend to deviate from the overall chemical stratigraphy; for example, the Espigon Member (DHFbs) has DHF II-like chemistry, while the Maja Member (sub-Poris Member) plots between DHF I and III.

The differing degrees of enrichment of Nb with increasing Zr are due to a varying role for residual titanite at some point in phonolite petrogenesis (Wolff et al., 2000), either during fractional crystallization or due to melting of pre-existing syenites with differing titanite fractionation histories (Wolff et al., 2000). It is also possible that DHF I and II phonolites could be related by titanite fraction of a different parental phonolite to DHF III (Fig. 6). No such relation exists between DHF I and III phonolites. A full discussion of petrogenesis is far beyond the scope of this paper, but the crucial point, fully supported by our expanded data set, is that the high-Nb/Zr and low-Nb/Zr phonolite types cannot be related by any simple evolutionary mechanism. Regardless of petrogenetic details, the salient feature of DHF magma chemistry is that two phonolite types that lack a simple evolutionary relationship persisted, or were repeatedly generated, throughout the lifetime of the DHF.

8. Evolution of the DHF eruptions, caldera complex and magma systems

8.1. Vent locations and dispersal patterns

The identification of proximal–distal facies variations and the isopach patterns of the major plinian fall deposits (Fig. 5) indicate DHF source vent locations in the area now occupied by the NE sector of the Las Cañadas Caldera, consistent with the caldera collapse model of Martí et al. (1994) and Martí and Gudmundsson (2000) in which the locus of phonolitic explosive activity migrated to the NE during the Upper Group cycles. Wind directions varied greatly (Fig. 5), but the most common dispersal directions were to the east and southeast, and only the western slopes of the island lack preserved DHF fall deposits. Pyroclastic flows were dispersed in all directions and commonly reached the sea. The extent of offshore dispersal is unknown, but seafloor ashes of similar ages occur widely in this region of the Atlantic (Moreno et al., 2001). PDCs varied widely in size and mobility: the most powerful lithic-rich flows (Ravelo and Abrigo ignimbrites) were dispersed radially and deposited widespread ignimbrite veneers in addition to complex valley-ponded deposits. In contrast, many smaller flows (e.g. Tajao, Antagas, and several ignimbrites within the Fasnia Member) were confined to one or two deep barrancos and left behind only valley-ponded deposits, although they are correlated with thin co-ignimbrite ash beds of much greater extent. For more detailed discussions of the transport and deposition of PDCs on Tenerife, see Edgar et al., 2002; Edgar, 2003; Brown and Branney, 2004a,b; Pittari et al., 2005, 2006.

8.2. Eruption styles

Despite their predominantly plinian character, the deposits of the DHF display a diversity which reflects a wide range of eruption styles and processes. The major members consist of complex sequences of intercalated fall, surge and ignimbrite units. Even individual phonolite fall deposits diverge in many ways from the homogeneous or simple reverse graded pattern which is considered the characteristic product of simple sustained plinian-style outbursts (Walker, 1981; Jurado-Chichay and Walker, 2001). Some ignimbrites (e.g. Tajao, Santo, Bueno) occur above thick, reverse-graded phonolite deposits as in the classic model of Sparks et al. (1973) and in these cases column collapse may have been caused by vent widening leading to an insupportable eruption intensity and magma discharge rate. However, the same eruptive sequences contain several intra-plinian ignimbrites and surges, indicating repeated and/or partial column collapse. Intra-plinian ignimbrite formation in the DHF indicates the influence of other, reversible, destabilizing factors, notably phreatomagmatic explosions and vent collapse. The high lithic content of many ignimbrites and ignimbrite facies testifies to the mechanical weakness of the conduit-vent systems.

Welded rocks occur in the Fortaleza Member (welded fallout sequence) and in proximal facies of the Santo ignimbrite (Fasnia Member) but are otherwise absent. The dearth of welded rocks in the DHF is in stark contrast with the extensive welded fall deposits and welded ignimbrites of the Ucanca and Guajara formations. This may partly reflect both the destruction of near-vent welded facies by caldera collapse and an increased role for cooling of the erupting magma by magma–water interaction, since
Phreatomagmatic deposits are far more abundant in the DHF.

8.3. Phreatomagmatism and the role of hydrothermal systems

The influence of external water is apparent among products of all the major eruptions and many of the minor ones. Basal phreatomagmatic fall and/or surge units occur in the Fasnia, Poris, Caleta and Batista Members. The basal sequences of the Fasnia and Caleta Members include vegetation-draping wet ashes that fell as mud, indicating high water-ash ratios. They are interpreted to record initial contact between rising magma and open water. Other members (e.g. Fortaleza, Tosca, Aldea, Arafo, Socorro, Hidalga and other members in the Cruz sequence) display a weaker phreatomagmatic influence in their basal portions. The persistent recurrence of these features is strong evidence for a long-lived or periodically re-established caldera lake in the DH source area. Phreatomagmatic deposits are also common in the middle and upper parts of many units (Taco, Cabezon, Espigon, Tosca, Aldea, Fasnia, Poris, Arafo, Caleta, Socorro, Benijos), indicating repeated interactions between rising magma and persistent external water.

The Aldea, Fasnia and Poris Members are rich in hydrothermally altered lithic fragments and display dramatic upsequence variations in their abundance. The stratigraphic complexity of these members can largely be attributed to conduit and vent instability which may have been enhanced by the long-term action of a subvolcanic hydrothermal system. There is a trend towards increasing simplicity in the internal stratigraphy of members in the upper half of the formation which might indicate destruction of the hydrothermal system by caldera collapse (see below), resulting in increased stability of feeder conduits. The Arafo and Caleta Members and most Cruz sequence members are relatively lithic-poor, and the dominant phreatomagmatic influence is the continued presence of a shallow, exhaustible caldera lake. However, up to 40% of the lithic clasts within the Abrigo ignimbrite are hydrothermally altered, indicating large-scale excavation of a pre-existing hydrothermal system along with seemingly complete evisceration of the magma chamber.

The Poris and Caleta Members both exhibit a return to a strongly phreatomagmatic eruption style after the main dry plinian phase which followed the initial phreatomagmatic activity. In both members, the top of the coarse plinian deposit is mantled by a lithic-rich fall layer interpreted to record vent-wall collapse, followed by accretionary lapilli-bearing fine ash surge deposits which indicate an immediate new influx of water into the vent. The most likely source is a caldera lake which was denied access to the magma during peak magma discharge associated with the dry plinian phase, perhaps by construction of a pyroclastic cone around the vent that was subsequently destroyed by vent-wall collapse recorded as the lithic layer. A similar lithic-rich fall deposit occurs at the top of the Arafo A plinian deposit and is immediately followed by the intra-plinian phreatomagmatic surge (Units B and C), which may indicate the same sequence of events. The strong stratigraphic similarities between these members (cf. Fig. 4e and g) therefore seems to indicate the persistence of a caldera lake, and vent-wall instability, which had a major influence on the course of DHF eruptions.

8.4. Caldera evolution

The Las Cañadas Caldera (LCC) has a complex history stretching back more than 1 million years. Its origins have long been controversial (Hausen, 1956; Bravo, 1962; Füster et al., 1968; Araña, 1971; Ridley, 1971) and recent debate has seen the elaboration of two competing models. In the lateral collapse model (Ancochea et al., 1990, 1999; Huertas et al., 2002), the caldera rim is interpreted as the head wall produced by one or more north-directed landslides, with vertical caldera collapse playing an insignificant role. The vertical caldera collapse model (Martí et al., 1994, 1997; Martí and Gudmundsson, 2000) identifies the primary mechanism as collapse into a magma chamber associated with large plinian eruptions, with secondary modification of the caldera depression by lateral collapse. The fundamental difficulty is that the structural floor of the caldera is unavailable for inspection due to burial by Teide–Pico Viejo lavas, and the debate has perforce revolved around less direct geologic evidence. The problem is compounded by different stratigraphic schemes for the Las Cañadas edifice and disputes about radiogenic dating and the timing of collapse events.

The results of the present study lend support to the vertical collapse model for the genesis of the caldera. Single explosive eruptions of 1–10 km³ volume DRE are frequently associated with formation of small to medium-size calderas (e.g. Krakatau, 1883; Katmai, 1912; Pinatubo, 1991). The volumes of several major DHF eruptions (Fasnia, Poris, Arafo, Caleta; Table 2), in addition to the Abrigo, are therefore consistent with caldera collapse. The large number of lithic-rich fall deposits and ignimbrites in the DHF indicates a high degree of conduit and vent instability. Lithic population variations in the climactic Abrigo ignimbrite (Pittari, 2004) suggest that radially-dispersed pyroclastic flow pulses were fed from several
vents along a ring fissure system. Vent-derived coarse lithic breccias at different levels in the Abrigo, Fasnia (Ravelo, Santo and Atojo ignimbrites), Poris (Quinta and Confital ignimbrites) and Caleta ignimbrites are inferred to record individual piecemeal caldera collapse events which contributed to the progressive enlargement of the LCC during the DHF period.

The persistence, or recurrence, of a caldera lake of sufficient size to produce the voluminous phreatomagmatic deposits that record high water/ash ratios in the Fasnia, Poris and Caleta Members clearly requires the existence of a closed depression(s) in Las Cañadas during DHF I–II time, over a period of some 70 ka. The required topography is more consistent with vertical collapse than with landsliding.

The most recent version of the caldera collapse model (Marti and Gudmundsson, 2000) focused on climactic caldera collapse events terminating each major volcanic cycle of the Upper Group. It is increasingly clear that caldera growth was more complex and incremental than this. The climactic eruption of the DHF (Abrigo Member) still represents the largest caldera collapse event, but at least three collapse events are likely earlier in the cycle (Fasnia, Poris and Caleta). Some indication of multiple caldera subsidence events comes from the scalloped geometry of the current topographic rim of the caldera. Although mass wasting and scarp retreat (e.g. Lipman, 1976, 1997) may have contributed to some of these irregularities, they could also reflect the outlines of smaller-scale collapse structures which contributed to the progressive enlargement of the LCC.

8.5. Temporal output and variations in magma types

Two phonolite magma types persisted, or were repeatedly generated, during the lifetime of the DHF. High-Nb/Zr magma, similar to that erupted during earlier explosive phonolitic cycles on Tenerife, produced most of the DHFs (except the Roque Member) and DHF III deposits, but was also available during the intervening 85 ka which were dominated by the low-Nb/Zr magma type (DHF I and II). This latter type first appeared with eruption of the Espigon pumice early in the DHF cycle, reappeared in the Roque Member at 347 ka, near the end of DHFs time, and reached a maximum flux with eruption of the Aldea and Fasnia Members at 319 and 309 ka. The Fasnia contains an intermixed component of high-Nb/Zr magma (Fig. 6), which is also represented in the 268 ka Poris Member (Edgar et al., 2002). Low-Nb/Zr magma (DHF II) again dominated the period between 268 and 234 ka. The latter finally disappeared with the onset of Cruz sequence activity at 234 ka, culminating in the Abrigo eruption at ≲196 ka. This pattern of episodes of alternating dominance of two phonolitic magma types, each of varying degrees of evolution, is perhaps difficult to reconcile with continuous co-existence of two distinct magma chambers throughout DHF time, but is consistent with repeated generation and fractionation of magma, or repeated melting of different protoliths, following structural re-arrangement after major eruptions (Fasnia, Poris, Caleta). The occurrence of basaltic magma in 5 of the 7 major members (Aldea, Fasnia, Poris, Caleta, Abrigo) attests to a crucial role for basalt in mobilizing, and perhaps generating, significant volumes of phonolitic magma through the transfer of heat to shallow levels within the island edifice. This is consistent with the ongoing shield-building basaltic volcanism in both the LCC and the rest of the island during the eruptive activity of the DHF. Following the major structural disturbance associated with the Abrigo event, phonolitic volcanism in Las Cañadas ceased until the last few tens of thousands of years when it began to re-appear during the eruptive activity associated with the growth of the Teide–Pico Viejo stratovolcano complex.

9. Conclusions

Detailed field mapping and volcanological analysis have produced the most detailed stratigraphy yet of the Diego Hernandez Formation, one of the major explosive phonolitic eruptive cycles of the Upper Group of Tenerife. This is augmented by new 40Ar/39Ar and corroborating (U–Th)/He geochronology, combined with critical analysis of previous geochronological work to produce a detailed chronostratigraphy which forms the basis for calculating eruption frequency, and for volcanic hazard prediction (Cas et al., in preparation). This work has demonstrated that the DHF cycle lasted for about 400 k.y., that phonolitic explosive activity began with relatively minor eruptions, and that the period of major explosive eruptions occupied the last ∼150 k.y. of the cycle, with significant repose periods between major eruptions. Most eruptions were complex, involving variations in eruption styles and dispersal processes of erupted products. Variations in eruption styles were caused by variations in eruption conditions, including the presence or absence of a caldera lake and hydrothermal system during each eruption. Two major phonolite magma types were repeatedly erupted during the history of the DHF. The dynamics of the two (single or multiple magma chambers) and life span of each magma type is uncertain. It is clear, however, that recurrent basaltic magmatism has played a major role in phonolite magma generation in this oceanic island shield volcano setting.
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