Lithostratigraphic analysis and geochemistry of a vitric spatter-bearing ignimbrite: the Quaternary Adeje Formation, Cañadas volcano, Tenerife

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Abstract

The 1.5 Ma Adeje Formation in SW Tenerife contains an ignimbrite sheet with remarkable textural and chemical complexity. A basal Plinian pumice-fall layer is overlain by a partly welded compound ignimbrite in which phonolitic pumice lapilli and dense obsidian spatter rags with irregular, fluidal-shaped margins are supported in a poorly sorted tuff matrix. The lower ignimbrite flow-unit contains accretionary lapilli in its upper part, overlain by an ash pellet-bearing fallout layer from a co-ignimbrite plume. The upper ignimbrite flow-unit comprises a locally welded massive lapilli-tuff that grades up into lithic breccia containing juvenile obsidian blocks and both cognate and vent-derived lithic blocks. Geochemically, the Adeje Formation shows two distinct juvenile populations that relate to crystal-poor and crystal-rich magma types. Crystal-rich juvenile clasts contain multiple compositions of ilmenite and magnetite, and crystal aggregates of bytownite (An_{79-86}). The varied assemblage of juvenile clasts reflects an eruptive style that may have involved rapid changes in magma chamber pressure associated with caldera collapse, and possibly the disruption of a lava-lake. The Adeje eruption started with a Plinian explosive phase that rained ash and pumice lapilli across SW Tenerife; followed by pyroclastic fountaining feeding density currents with explosive ejecta of juvenile glassy material producing the coarse, spatter-bearing ignimbrite facies. A short pause between pyroclastic density currents is recorded by the co-ignimbrite ash and pellet-fall bed. The climactic phase of the eruption probably involved caldera subsidence as recorded by a widespread massive heterolithic breccia.

Keywords: Tenerife, explosive eruptions, pyroclastic density current, phonolite, spatter, ignimbrite

1. Introduction

Las Cañadas volcano on Tenerife has a long history of explosive Plinian eruptions that have repeatedly dispersed ash and pumice across the island and sent catastrophic pyroclastic density currents cascading down the flanks. It is an ideal place to study the products of explosive eruptions on intraplate ocean-island volcanoes: its history is recorded in a spectacularly well-exposed and dissected pyroclastic apron, the Quaternary Bandas del Sur apron, which covers more than 200 km^2 of the southern coastal desert (Fig. 1; Bryan et al. 1998; Brown et al. 2003). More than 35 soil-bound explosive eruption-units are recorded within this 1.8–0.13 Ma succession, including abundant ash and pumice fall deposits intercalated with a variety of welded and non-welded ignimbrites, phreatomagmatic tuffs, a debris-avalanche deposit (Dávila-Harris et al. 2011), and the products of smaller flank and rift-zone eruptions. Major eruption-units can be traced over irregular topography, allowing detailed investigation of magma chamber process, eruption styles and pyroclastic emplacement processes (e.g. Pittari et al. 2004; Brown and Branney 2004).

This paper documents the 1.559 ± 0.014 Ma Adeje Formation (Fig. 2) an unusual spatter-bearing ignimbrite in the Bandas del Sur Group that displays marked textural, depositional and geochemical variability. It is one of the oldest exposed ignimbrite sheets on the island. We describe its internal stratigraphy, vertical and lateral lithofacies variations, geochemistry and petrology (Fig. 2), and give the first interpretation of its eruption, transport and depositional mechanisms. The Adeje Formation shares many physical and geochemical similarities with other lower Pleistocene ignimbrites (e.g., Gaviotas, Pegueros and Derriscaderos ignimbrites, Dávila-Harris 2009) and with younger (e.g. Arico, Bryan 1998; Brown et al. 2003) ignimbrite sheets on the island, suggesting a similarity of activity for > 1.5 Ma. This study helps better define the processes and products of large explosive eruptions on the island.

2. Geological Setting

The intraplate ocean-island volcano of Tenerife lies in the northeast Atlantic Ocean, 300 km off the coast of Morocco. Subaerial eruptions have occurred since the Miocene at three deeply eroded Miocene to Pliocene basaltic massifs (‘Old Basaltic Series’ of Fúster et al. 1968; Ancochea et al. 1990) and from an overlying, younger central edifice, Cañadas volcano, which includes more differentiated products (Martí et al. 1994). Cañadas volcano has been active for >3 Ma and has produced numerous caldera-forming ignimbrite eruptions (e.g. Martí et al. 1997; Ancochea et al. 1999; Brown et al. 2003) as well as sector-collapse landslides normal to three rift zones that radiate from the summit caldera (Fig. 1). Most research on the Quaternary explosive volcanism has focussed on the younger (0.65 – 0.13 Ma) upper part of the Bandas del Sur pyroclastic apron of Cañadas volcano, best exposed in the southeast (Alonso 1989; Bryan et al. 1998; Brown et al. 2003; Edgar et al. 2007). In contrast, this work concerns the older (~1.8 to 0.8 Ma), 'lower' Bandas del Sur Group (Brown et al. 2003: Dávila-Harris 2009) exposed between Los Cristianos and Playa de San Juan in southwest Tenerife (Fig. 2). There, a variety of predominantly phonolitic pyroclastic fall deposits and ignimbrites are intercalated with basaltic to phonolitic lavas, gravel, and palaeosols as well as the products of local flank and southern rift-related eruptions (Dávila-Harris 2009).

2.1 Previous studies of ignimbrites around Adeje

No single exposure around Adeje reveals the complete pyroclastic succession—most Tenerife ignimbrites are discontinuous due to localised deposition and erosion (e.g. Brown and Branney 2004). The succession was originally divided informally into: older undifferentiated pyroclastic units (Fúster et al, 1994) overlain by the 'Adeje-type Ignimbrites' (described as a non-welded to partly welded '*siena tostada*' unit SW of Adeje); in turn overlain by a dark grey 'Taucho Ignimbrite'; and an upper eutaxitic, greenish 'Playa de San Juan Ignimbrite' (Fúster et al. 1994; Fig. 1).

Published K-Ar and $^{40}Ar/^{39}Ar$ dates of the 'Adeje-type ignimbrites' range from 1.54 ± 0.28 to 1.68 ± 0.10 Ma (Fúster et al. 1994; Ancochea et al. 1999; Huertas et al. 2002) but suffer from low precision (e.g. errors up to 18 %), unclear stratigraphic locations and apparently conflicting dates for individual units. The Adeje ignimbrite was taken to be part of the Arico Formation (Middleton and Cas 2004), also locally orange with obsidian clasts (Schmincke and Swanson 1967; Bryan et al. 1998), but the latter is now known to be much younger (668 ± 4 ka; Brown et al. 2003). Descriptions and limited geochemical data from the 'Adeje red ignimbrite' were presented by Wolff (1983), who noted the presence of obsidian and poorly vesicular juvenile clasts, welding, and similarities with ignimbrite 'F' of Arico (now known as the Arico Formation; Brown et al. 2003).

3. Study methods and nomenclature

As part of a broader initiative to document the pre-700 ka pyroclastic stratigraphy of southern Tenerife (Dávila-Harris, 2009), sixty-five pyroclastic sections in SW Tenerife (Fig. 1) have been logged in detail. Eruption-units, pyroclastic lithofacies, palaeosols and erosion surfaces were defined, characterised and traced-out, noting lateral variations, and the lithofacies and field relations were interpreted (lithofacies descriptions in Online Resource 1). This paper adopts existing stratigraphic names where possible but to avoid confusion, the loose grouping ‘Adeje-type ignimbrites’ (Fúster et al. 1994; Huertas et al. 2002) is dropped and the term Adeje Formation is defined for a specific, regionally traceable unit (following the lithostratigraphic scheme of Brown et al. 2003, 2010, and Dávila-Harris 2009).

4. The Adeje Formation

4.1 Stratigraphy

The Adeje Formation is a distinctive, lithologically heterogeneous ignimbrite sheet in the lower Bandas del Sur Group (Fig. 3). It outcrops across southwest Tenerife from Las Americas in the south, to Playa de San Juan in the northwest (Fig. 1, inset). The most complete type section occurs at Barranco de las Galgas, Playa Paraíso (Fig. 1), where it rests upon a well-developed palaeosol on the Fañabé Formation, and is unconformably overlain by basalt lava and by the San Juan Formation (Figs. 3 and 4 log 7-9). The intricate erosive contacts between the two formations (e.g. at the type section; Fig. 5a) are thought to reflect erosion and local regolith formation of a lithified Adeje ignimbrite substrate at a desert coastal platform, prior to emplacement of the San Juan Formation ignimbrite: (see Online Resource 1 figures). The Adeje Formation is overlain by the erosive base of the San Juan Formation ignimbrite with no intervening soil at Barranco de Erques (Fig. 4 log 7), but the two formations are interpreted to be distinct eruption-units because (1) they are separated by a basalt lava, at Punta Negra (Online Resource 1), and (2) the Adeje Formation is locally overlain by phonolite lava resting upon a baked palaeosol near Barranco del Agua (Fig. 6), indicating a significant hiatus between the Adeje and San Juan eruptions. Moreover, tracing these units up-slope, irregular contacts persist and a paleosol is locally exposed (Figs. 1 and 4 log 7).

At the type section, the Adeje Formation is subdivided into four lithostratigraphic units: layers A-D.

Layer A is a 1 m-thick pumice layer, and is overlain by a compositionally zoned, compound ignimbrite sheet, comprising a 3–20 m thick, slightly welded ignimbrite flow-unit (layer B) with a pale-cream, non-welded base that is separated from an upper ignimbrite flow-unit (layer D) by a sub-horizontal ash layer (layer C; Figs. 3 and 4). Single K feldspars separated from pumice in flow-unit 2 (layer D), at Adeje have yielded an $^{40}Ar/^{39}Ar$ date of 1.559 ± 0.014 Ma (2 σ) (Pringle, in Dávila-Harris, 2009).

Within the Ucanca caldera wall succession (Fig. 1), the Adeje ignimbrite is temporally equivalent to the lower part of the Upper Group, possibly to units in the Guajara Formation (Martí et al. 1994). An ignimbrite within the lower part of the Guajara Formation contains large, black crystal-rich juvenile clasts in a partly welded matrix, and has yielded a K-Ar age of 1.5 Ma (Martí pers. comm.) and may be a proximal equivalent of the Adeje Formation.

4.2 Individual layer description

Layer A: massive to diffuse parallel-bedded ash and pumice lapilli

Layer A of the Adeje Formation rests on a palaeosol and is up to 1 m thick. The base of layer A comprises a 3 cm-thick pumiceous ash that coarsens upwards into a layer ~15 cm thick, of coarse ash to fine pumice-lapilli, in turn overlain by 80 cm thick layer of massive and diffuse parallel-bedded pumice lapilli (mL and dbpL on Fig. 4, log 8 and Fig. 5). Pumice lapilli are 3 to 5 cm, green to grey, angular, well-sorted, framework-supported, crystal-poor and partly zeolitised. They are accompanied by subordinate, smaller, black and grey basalt and phonolite angular lithic lapilli. The layer thickens towards the northwest of Adeje, indicating a southwest-trending dispersal axis (Fig 1). The upper contact of layer A is sharp and scoured.

Interpretation: Layer A records the opening phase of the Adeje eruption, with the development of a

Plinian eruption column that dispersed ash and phonolite pumice lapilli widely over southwest Tenerife, >10 km from source. Its fallout origin is indicated by the very good sorting, pumice angularity, framework support, parallel bedding, and systematic lateral changes in grainsize. The finer grained basal part records a lower, initial column, and the upward coarsening records increasing column height as the eruption waxed. The diffuse bedding above this records unsteady fallout, probably caused by short-lived fluctuations in the height of the eruption plume (e.g. Rosi et al. 1999).

Layer B: massive lapilli-tuff and lithic breccia

At the type locality, layer B is ≤3 m thick but varies up to 6 m thick, and rests upon the lower pumice-fall deposit. It comprises predominantly massive lapilli-tuff (mLT; Fig. 6) with extensive lenses of lithic breccia (mlBr), < 2 m thick and traced laterally for up to 500 m. Rounded, variably altered, pumice lapilli and angular lithic lapilli are supported in a pale brown ash matrix composed of glass shards and abundant (≤ 5-10 %) crystal fragments 0.2 mm to 5 mm across (Fig. 7a). The lithic clasts reach 1 m in diameter and include phonolite, basalt, volcanic glass and rare syenite. The lowermost few centimetres of layer B are commonly finer-grained (Fig. 3) and diffuse-stratified, with imbricated lithic lapilli and local splay-and-fade stratification (Branney and Kokelaar 2002). This locally grades upwards and laterally into the massive lapilli-tuff. Locally, layer B is pale cream and diffuse-bedded, with abundant grey to green vesicular pumices (Fig. 5), and grades into massive heterolithologic breccia (≤2 m thick) composed of black, glassy and crystal-rich juvenile blocks (Fig. 7). The suite of petrologically varied juvenile clasts is described in Table 2 of Online Resource 1.

Locally, the massive lapilli-tuff and the lithic breccias of Layer B (mlBr, Fig. 7) contain abundant non-vesicular glassy juvenile clasts, including blocks of porphyritic glass, rich in ‘swallow-tail’ textured alkali feldspar. The proportion of juvenile clasts increases with height in layer B to form nearly clast-supported domains of juvenile-clast breccia (up to ~40 vol. %), in which the juvenile blocks reach up to a meter in diameter, and range in shape from sub-angular to sub-rounded, with fluidal, prismatic-jointed margins. They variously exhibit clastogenic, mingled, and partly devitrified (spherulitic texture) in a phonolitic glassy groundmass. Locally (e.g. Barranco de Erques; Fig. 1), poorly developed fiamme and obsidian with oblate shapes (Fig. 7b) define a eutaxitic texture (emLT), also seen in thin section. Welding generally increases with height within layer B (Fig. 7c), but varies laterally and vertically, with welding zones ranging from 0.25 to 3 m.

Interpretation: The initial Plinian phase transformed into pyroclastic fountaining with the generation of density currents downslope and across SW Tenerife, as recorded by the very poor sorting, abraded and rounded pumice lapilli, abundant fines and lateral variability in layer B. The density currents brought in the denser, green pumice clasts and obsidian blocks, as recorded above the diffuse-stratified lapilli-tuff facies. The upwards change from diffuse-stratification to more massive, coarser-grained block-rich lapilli-tuff records a change from the initial impingement of rather unsteady, leading reaches of the current with lower and variable rates of deposition, to the establishment of more steady, sustained granular fluid-based current undergoing rapid deposition at a fluid-escape dominated flow-boundary zone (Branney and Kokelaar 2002). As the eruption gradually waxed, coarser-grained and denser juvenile material was progressively fed into the current. The variations in the erupting magma, may record localized changes in magma withdrawal dynamics, with denser ejecta derived from deeper, less volatile-rich parts of magma chamber. Other interpretations such as conduit degassing before fragmentation allowing for longer periods of residence of magma batches in the conduit prior to explosive extrusion, could also be an alternative (Shea et al. 2012; Alfano et al. 2012). During transport and deposition, the dense glassy juvenile clasts are thought to have behaved similarly to lithic blocks with which they are associated, while simultaneously receiving partial support from buoyancy provided by the density of the enclosing fluid, particle collisions and related segregation processes (Branney and

Kokelaar 2002). The massive lithic breccias record influxes of lithic material from decrepitating conduit walls, or were entrained by the density current during the journey from source. The upward increase in welding is interpreted to record a progressive increase in the temperature of the sustained density current with time as the current waxed, and as the proportion of larger, hotter juvenile components increased. Some of the fiamme (e.g. Fig. 7b) are thought to represent former poorly vesiculated, low-viscosity hot clasts rather than true pumice that collapsed during load welding. A similar origin has been inferred for glassy fiamme in the Arico Formation and elsewhere (Bull and McPhie 2007 and references therein).

Layer C: ash aggregate-bearing

Layer C is a sub-horizontal ash aggregate-bearing layer 25 cm thick. At Lomo del Cuchillo (Fig. 1) it is traceable for hundreds of metres (Fig. 6). Its lower contact with underlying massive lapilli-tuff (mLT) and breccias (mlBr) varies from gradational to sharp (Fig. 8a). The layer comprises massive lapilli-tuff with accretionary lapilli (mLTacc; Fig. 9b) that grades upwards into a clast-supported stratified pellet-layer (sLTpell) that has a sharp upper contact. Above this is a 10 cm thick layer of clast-supported coarse-ash to fine-lapilli, commonly lithic-rich with a sharp upper contact with layer D.

Interpretation: The lower part of layer C (accretionary-lapilli bearing massive lapilli-tuff) is interpreted as ignimbrite, deposited from a granular flow-based pyroclastic density current (Branney and Kokelaar 2002) as indicated by the very poor sorting, matrix-supported rounded pumice and lithic lapilli, and absence of tractional stratification. The overlying, laterally continuous layer of framework-supported ash pellets is interpreted to be of fallout origin, as it mantles topographic irregularities. Therefore, the fining-upwards transition into this layer from the underlying accretionary lapilli-bearing ignimbrite records the last stages of the density current, which probably ended as a dilute and slowly moving ash cloud that deposited accretionary lapilli, which had grown in the current after being introduced as pellets from overlying lofted co-ignimbrite plume, as described for similar sequences elsewhere on Tenerife (e.g. Brown and Branney 2004; Brown et al. 2010). The presence of ash aggregates is not necessarily indicative of phreatomagmatism, as sufficient moisture may exist in a co-ignimbrite plume on this oceanic island to cause particle agglomeration. The pellet-fall layer records a brief hiatus (minutes to days) between the two major density currents that deposited layers B and D. There is no evidence of rill-erosion, reworking or soilification in this soft layer that would point to a protracted time-gap.

Layer D: massive lapilli-tuff; massive lithic-breccia; massive agglomeratic tuff

Layer D is a dark orange, massive lapilli-tuff and lithic breccia that locally grades into diffuse-bedded lapilli-tuff with sporadic lenses of black juvenile blocks. It is well exposed at several localities, near Caldera del Rey, at Costa Adeje, Barranco del Agua and Playa Paraíso (Fig. 1). It reaches 10 m thick but is typically ~4 m and it exhibits fines-rich, diffuse-stratified lapilli-tuff (dsLT) all within a lithic- and crystal-rich matrix. A prominent agglomeratic lapilli-tuff facies (mAgLT; Fig. 8a), 3 to 4 m thick, contains ≤ 20% black, poorly-inflated, sometimes breadcrusted juvenile clasts <0.5 m in size (Fig. 9a). These vary from sub-rounded to angular, fluidal-shaped and elongated spatter-like, supported in an orange to dark grey matrix (Fig. 8b). Many of the clasts contain accidental lithic lapilli. Crystal concentrations of alkali feldspar locally reach 80% in some juvenile clasts (e.g. sample AJ-65; Online Resource 2), and some show mingling of pale-green glass with black, crystal-rich bands (Table 2 Online Resource 1). The coarse agglomeratic lithofacies that is common at near coastal exposures (Fig. 8b) commonly shows clast imbrication and locally grades into massive lapilli-tuff (emLT) with a dark grey, weakly eutaxitic matrix. The top is widely scoured, usually eroded or in irregular contact with the overlying unit (Figs. 5a, 6 and 8a).

Interpretation: Layer D represents the climactic phase of the Adeje eruption. Deposition was initially from a fully dilute pyroclastic current (as indicated by tractional-stratified lithofacies, dsLT), onto the relatively flat upper surface of layer C. Through time this current evolved into a granular-fluid based density current (as indicated by the massive, very poorly sorted lithofacies, mLT to mAgLT), probably with a fluid-escape dominated flow-boundary zone (Branney and Kokelaar 2002). We infer that this change with time probably reflects an increase in mass-flux as it was accompanied by waxing current competence (indicated by increasing size of the coarse-tail with height in layer D). The current increasingly was able to transport large lithic clasts and dense juvenile spatter-rags, recorded by the lithic layers and cauliform or bread-crusted blocks respectively. Ropey surfaces indicate that some of the juvenile clasts were hot and ductile during fragmentation and transport prior to quenching. Crystal-rich swallowtail textures in anorthoclase and sanidine crystals, surrounded by glassy groundmass, may record rapid cooling of phonolite melt (Oriano et al. 2010). Towards the south of Adeje, layer D grades into a palaeosol baked by phonolite lava, elsewhere, it is unconformably overlain by the Caldera del Rey tuff and the San Juan Formation (Fig. 2).

5. Geochemistry

Twenty-eight juvenile clasts were selected for geochemical analysis via X-ray fluorescence or made into thin sections and polished thin sections of crystal separates for electron microprobe (Fig. 3). The freshest pumice samples were selected, rinsed with deionised water, oven-dried and the altered exteriors were removed.

5.1 Whole rock chemistry

Twelve samples of the freshest material were taken for bulk geochemical analyses from the type section of the Adeje Formation (Fig. 3) at El Pris in southwest Tenerife (data in online repository), and analysed on a Phillips PW 1400 at the Geology Department, University of Leicester, using standard techniques described by Dávila-Harris (2009).

Juvenile clasts show considerable variation in major elements (SiO_2 ranges from 51.1 to 65.7 wt.%; CaO from 0.6 to 8.3 wt.% and MgO from 0.3 to 2.5 wt.%; Fig. 10a). The highest SiO_2 value of 68.3 wt.% (from a bulk ash-fall deposit, AP-48) likely represents silicification of the sample despite efforts to avoid this, a conclusion supported by the low alkali values for this sample. Trace elements show considerable variation, nearly one hundred-fold in some cases; Zr varies from 283 to 1510 ppm (Fig. 10b), Sr from 16-1420 ppm (Fig. 11), and Ba from 51-1928 ppm (Fig. 10c). The Zr data suggests two discrete populations, with a 'high-Zr phonolite' and 'low-Zr phonolite' similar to that reported by Edgar et al. (2002). Plots of incompatible vs. compatible elements (Fig. 10) reveal that the data are not readily explained by simple mixing between a high Zr phonolitic component and a less fractionated equivalent, (e.g. Edgar et al. 2002). The relationship of high Sr and Ba in the crystal-rich samples, intermediate Sr and Ba in the mingled samples, and low Sr and Ba in the crystal-poor samples suggests that, to some degree, the bulk compositional variability is controlled by the presence of crystal-rich material, potentially removed from a 'mushy' zone beneath the magma reservoir (e.g. Bachmann et al. 2002). This inference is supported by the higher Zr in the crystal-poor samples: given the reluctance of zircon to crystallise from phonolitic melts, increased crystallinity will act to dilute the abundance of zirconium via a reduction in the proportion of its only repository, the glass.

5.2 Mineral Chemistry

Pumice and vitric clast samples of Adeje ignimbrite and fallout pumice lapilli were crushed, wet-sieved and separated with heavy liquids to concentrate mineral phases. Crystals were analysed with a JEOL JXA-8600S electron microprobe at the University of Leicester, with operating conditions of 30 nA current, 15 kV and a beam diameter of 10 µm. The Adeje Formation contains alkali-feldspar, plagioclase, ilmenite, magnetite, augite, kaersutite, biotite, rare olivine and apatite (see Online Resource 2).

5.3 Feldspar

Adeje Formation feldspars reach 5 mm in size, commonly contain melt inclusions and are mostly euhedral. Most occur as individual crystals, but glomerocrysts occur in some samples (AJ64 and AJ65;). The range of feldspar compositions in the Adeje Formation is similar to that observed from other Tenerife phonolites (Bryan et al. 2002; Bryan 2006; Triebold et al. 2006) and compositions produced in experiments on Tenerife phonolites (e.g. Andújar et al. 2008). Feldspar compositions in flow-unit 2 show more variation than those in flow-unit 1. The Adeje Formation has few feldspars with compositions of An_{45}-An_{52} (Fig 13), a compositional gap reported for the feldspars in the Poris Formation inferred to discriminate between plagioclase populations from mafic and silicic magma sources (Edgar et al. 2002). Crystal aggregates are dominated by calcic plagioclase (An_{79}-An_{86}), first reported from the ‘red ignimbrite’ by Wolff (1983) and found in other Tenerife ignimbrites; the Abades and Poris formations ('Abades Member' and 'Pedrigal ignimbrite' of Bryan et al. 2002). Calcic plagioclase crystals have compositions similar to those in historic basanites (Ablay et al. 1998; Triebold et al. 2006; Fig. 12) and require an origin in a mafic magma.

5.4 Geothermometry

To investigate the possible influence of magma composition on welding, magmatic temperatures were estimated using the Fe-Ti oxide thermometer of Sauerzapf et al. (2008). The criteria of Bacon and Hirschmann (1988) were used to test for equilibrium between ilmenite and magnetite, and all samples except one (AJ60) had at least one pair of compositions that were in equilibrium (Online Resource 2).

To determine the representative temperature for a sample, at least ten ilmenite-magnetite pairs were analysed, and the results averaged (errors shown on Fig. 11 represent the standard deviation of the ten or more measurements).

Temperature estimates for the Adeje Formation range from 798 ± 14^{o}C (fO_2 -13.8) to 1009 ±12^{o}C (fO_2 -9.9). These are in good agreement with magmatic temperatures reported from other Tenerife phonolites (Wolff and Storey 1983; Wolff 1985; Ablay et al. 1998; Bryan et al. 2002). Oxides from the basal pumice fallout deposit (sample AJ58) returned a temperature of 829 ± 10^{o}C (fO_2 -12.9) and temperatures increase upwards in flow unit 1 (layer B) to 926 ± 11^{o}C (fO_2 -11). Flow-unit 2 (layer D) exhibits significantly more variability in ilmenite and magnetite compositions (Online Resource 2). Both ilmenite and magnetite occur as multiple compositional modes in two samples of glomerophyric bands within juvenile clasts from layer D (AJ64 and AJ 65; Fig. 11). Each mode is consistent with being in equilibrium using the criteria of Bacon and Hirschman (1988), and they yield average magmatic temperature estimates independent of error of 926 ± 6^{o}C (fO_2 -11) and 942 ± 20^{o}C for sample AJ64; and 822 ± 17^{o}C, 871 ± 5^{o}C and 979 ± 16^{o}C (fO_2 -10.4) for sample AJ65 (Fig. 11). The stratigraphically highest sample in flow-unit 2 (sample AJ67; Figs. 3 and 11) yields an average magmatic temperature estimate of 798 ± 14 ^{o}C (fO_2 -13.8). Both the highest and lowest inferred temperatures are derived from the upper ignimbrite (Fig. 11) illustrating no simple relationship between juvenile cargo and welding intensity.

5.5 Overview of geochemistry

The Adeje Formation represents a complex eruption in terms of its physical and geochemical characteristics and here we provide only a preliminary view of its geochemistry. The crystal-poor juvenile pumice is present throughout the Adeje Formation, being the dominant component of the fallout at the base of the Formation and also occurring at the very top of flow unit 2. This juvenile type reflects the most evolved magma (highest Zr, 913-1510 ppm), which was stored at between 798 and 830 ^{o}C. It contains a variety of feldspar compositions (Fig. 12) but notably lacks anorthitic plagioclase. The crystal-rich magma exhibits more compositional variability than the crystal-poor magma and is found throughout both flow units 1 and 2. The crystal-rich magma may have multiple equilibrium compositions of ilmenite and magnetite (Fig. 11) with the majority of temperatures in the crystal-rich juveniles being slightly higher (840-979 ^{o}C) than those from the crystal-poor juveniles. Zr content in the crystal-rich juveniles is significantly lower than the crystal-poor juveniles (283-558 ppm) and Ba more than an order of magnitude higher (reaching 1928 ppm). The decreased Zr and increased Ba in the crystal-rich juveniles suggest that these juveniles are not merely more crystallised versions of the crystal-poor juvenile but likely are accumulative in feldspar (e.g. Edgar et al. 2002). Glomerocrysts of anorthitic plagioclase (e.g. Fig 12) are found within the crystal-rich juveniles in the upper flow unit of the Adeje Formation with bulk compositions elevated in CaO and Sr (e.g. AJ66). Such bulk variations are also observed in V indicating that the mafic glomerocrysts contain iron oxides, an interpretation that is supported by the two juveniles that contain the largest proportion of high-An plagioclase (e.g. AJ65, 66 Fig. 12) also having the highest temperatures (Fig. 11).

In conclusion, the variety of compositions in the Adeje Formation may be explained via co-eruption of a crystal-poor magma and a similar, but more crystal-rich magma (potentially a mush equivalent). The high-anorthite glomerocrysts require a mafic source but the relationship between this mafic magma and the cause of explosive eruption remains speculative.

6. Discussion – eruption style

Eruption summary

After a repose period of ~26 ka, recorded by the well-developed palaeosol on the Fañabé Formation (Fig. 2), the Adeje eruption began with a phonolitic Plinian eruptive phase, recorded by the presence of bedded ash and pumice lapilli, layer A (Fig. 13a). This phase was followed by pyroclastic fountaining, generating a pyroclastic density current that flowed 15 km to the coast and passed out to sea (layer B). Vent erosion may have occurred (caldera collapse initiation), coupled with increase in mass flux and the inability of the column to become buoyant. Lithic and juvenile blocks were entrained in the pyroclastic density current during this phase and the temperature of the current increased, as recorded by the upward increase in welding intensity. A co-ignimbrite plume developed above this sustained density current, and ash pellets fell out from it into the ground-hugging current, where they grew into accretionary lapilli (lower part of layer C). A brief cessation in the pyroclastic density current, during which pellets continued to fall from the residual co-ignimbrite plume, is recorded by the thin pellet fallout layer within layer C. This pause may equally reflect a shift in the dispersal of the density currents to another sector of Cañadas volcano. The pause was brief as there is no evidence for local rill erosion, reworking or soilification at this horizon (Fig. 13c), and was followed by the climactic phase of the Adeje eruption, when a resumption in pyroclastic fountaining generated a high-competence, pyroclastic density current that carried hot spatter and lithic blocks (Fig. 7c and 8), from the source in Cañadas caldera (Fig 13). It is recorded by the 10 m thick coastal ignimbrite, layer D, while much of the pyroclastic material may have overpassed the coastal plain and ended in the ocean. Layer D has an eroded top and its original thickness is not known. A record of the post-climactic waning phases of the Adeje eruption has not been preserved.

The agglomerate-bearing ignimbrite facies (mAgLT)

Spatter-like clasts have been generated from a variety of magma compositions, and are primarily found in proximal settings (Turbeville 1992; Carey et al. 2008). The origins of spatter-like clasts in ignimbrites have been ascribed to disruption of a lava lake (Mellors and Sparks 1991), or rapid changes in the depth of magmatic evacuation resulting in eruption of magma with different properties (e.g. Branney and Kokelaar 1992; Perrotta and Scarpati 1994; Allen 2005). Changes in clast density have also been attributed to magma residence times in the conduit and thus a variation in degassing prior to fragmentation will probably cause density variations (Sable at al. 2006; Shea et al. 2012). By contrast, the dense and spatter-like clasts in the Adeje ignimbrite are present at the most distal exposures on the island, with an increased abundance towards the top of flow-unit 2 (Fig. 8). The spatter-rags, irregular, fluidal, contorted, and bread-crusted clast morphologies are extremely delicate and are matrix-supported in massive ignimbrite. The margins of the fluidal clasts indicate that they cooled in-situ and were not significantly modified by transport within the current (e.g. Dufek and Manga 2008). The relatively low vesicularity of the spatter-like clasts suggests that they are the product of a volatile-poor magma, which may have been extracted following a rapid pressure drop in the conduit during the eruption. This together with the occurrence of abundant angular lithic clasts in the deposit suggests a phase of caldera subsidence or rapid vent flaring (e.g. Branney and Kokelaar 1992; Perrotta and Scarpati 1992; Fig. 3). Kokelaar et al. (2007) noted an association between spatter-bearing pyroclastic deposits and flooded calderas and suggested that their generation might be the result of phreatomagmatic phases during caldera subsidence. However the incipient welding and vesicular nature of the juvenile components within the Adeje suggest instead a magmatic eruption mechanism for the Adeje ignimbrite.

A minor juvenile component of the Adeje ignimbrite are clastogenic, ropy-textured clasts that are commonly produced during fire-fountaining eruptions (e.g. Mellors and Sparks 1991) and are found in proximal regions. Although no proximal deposits of the Adeje ignimbrite are known, we infer that fire fountaining was occurring during the eruption, either synchronously with the pyroclastic currents or during the hiatus recorded by layer C (Fig. 3; top of layer B and through most of layer D). The variety of juvenile morphologies and chemical heterogeneity (see above) observed from the Adeje Formation indicates a complex eruption with a fluctuating eruptive style. Similar spatter-bearing lithofacies are observed in other ignimbrites on Tenerife, including the older Gaviotas ignimbrite (Fig. 2), the Arico ignimbrite (Bryan et al. 1998; Brown et al. 2003) and the Pegueros and Derriscaderos ignimbrites

(Dávila-Harris 2009). The repetition of similar lithofacies in numerous ignimbrites suggests that the process is relatively common on Tenerife.

7. Conclusions

The phonolitic 1.559 ± 0.014 Ma Adeje Formation is the product of one of the oldest recorded ignimbrite-forming explosive eruptions from Cañadas volcano. It began with an initial Plinian explosive phase that deposited ash and pumice across SW Tenerife. This column foundered and generated sustained pyroclastic density currents that travelled 15 km to the ocean, and deposited a widespread ignimbrite sheet. The climactic phase of the Adeje eruption is recorded by a partly welded ignimbrite that contains massive heterolithic breccias generated by caldera collapse and/or an intense phase of conduit-wall erosion. The upper ignimbrite flow-unit also contains abundant vitric spatter rags as well as angular dense juvenile blocks in addition to pumice clasts. These may reflect a phase of proximal spatter accumulation, which was then disrupted during the peak of explosivity associated with caldera subsidence. The Adeje ignimbrite contains a record of geochemical complexity with crystal-rich and crystal-poor juvenile clasts mingled throughout the deposits. The crystal-rich juvenile clasts are inferred to record disruption of a magmatic crystal mush. The presence of glomerocrystic aggregates of bytownitic plagioclase indicates a mafic involvement in the eruption. Despite being one of the oldest ignimbrite sheets on Tenerife, the Adeje Formation shares many physical and geochemical similarities with the products of other large explosive eruptions on the island. This suggests that Plinian eruptions on Tenerife consistently follow similar paths, and this study can reasonably be used to help define the likely hazards associated with such events.

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Tables

Table 1 Lithofacies code abbreviations (Modified after Branney and Kokelaar, 2002)

Figures

Fig. 1 Map of the southwest flank of Las Cañadas volcano, Tenerife (inset). UTM grid reference intervals 1 km.

Fig. 2 Simplified vertical stratigraphy of the Lower Bandas del Sur Group in southwest Tenerife showing location of the Adeje Formation. Not all field relationships are shown. Vertical and grainsize scale are schematic. Radiometric Ar-Ar Age in Ma: *this study. References on inset column: A, Edgar et al. 2007; B, Huertas et al. 2002; C, Bryan et al. 1998.

Fig. 3 Log and main lithofacies descriptions across a composite section of the Adeje Formation in the area between El Puertito and Playa Paraíso, southwest Tenerife. UTM: 326436 / 3110688.

Fig. 4 Selected logs of the Adeje Formation (from a total of 65) in southwest Tenerife. Locations of logged stratigraphic sections see Fig. 1, UTM coordinates on inset table. Thicknesses and grain-size scale are schematic.

Fig. 5 a) Type section of the Adeje Formation at Playa Paraíso. One metre-thick pumice-fall deposit (layer A) rests on palaeosol, overlain by diffuse-stratified ignimbrite (layer B). Thin pale layer, fines-rich lapilli-tuff represents layer C, overlain by massive agglomeratic tuff (layer D). b) Pumice-fall deposit (layer A) at the base of the Adeje Formation, Barranco de Erques. Scale ruler in all photos is 1 m long with 10 cm intervals.

Fig. 6 The Adeje Formation at Barranco del Agua. a) 12 m thick exposure of the Adeje ignimbrite layers B, C and D overlying unconformably older pyroclastic units. Note pristine sub-horizontal flow-unit boundary layer (C) between thick massive lapilli-tuff. b) Layers B, C and D overlain by phonolite lava, road to Costa Adeje resort.

Fig. 7 a) Base of ignimbrite layer B of the Adeje Formation at upper Barranco del Agua resting on top of pumice-fall layer A. b) Detail of partly welded lapilli-tuff in layer B. c) The Adeje Formation at El Puertito showing altered pumice-fall deposit at the base, overlain by lithic-poor ignimbrite and heterolithologic breccia, grading upwards into partly welded tuff. Inset: close-up of scour surface and lithic breccia on plate c.

Fig. 8 The Adeje ignimbrite at El Puertito. a) Layer B showing mLT overlain by massive breccia rich in juvenile blocks, followed by layer C. Layer D on top grading into massive agglomeratic tuff pinching-out towards the right-hand side of picture, rucksack is 0.5 m. b) Close-up to imbricated, crystal-rich juvenile blocks, marked with a ‘J’. Pristine black, glassy, aphyric spatter-like blocks of irregular, fluidal shapes are common in coastal exposures. Scale shows 30 cm.

Fig. 9 a) Breadcrusted juvenile block forming massive agglomeratic lithofacies, layer D. b) Accretionary-lapilli horizon in layer C associated to pellet fallout may record flow-unit boundary. c) Detail of juvenile clast with crystal-rich and aphyric glassy texture. Scale shows cm.

Fig. 10 a) Total alkali vs. silica content plot (TAS, Le Bas 1986) for samples of the Adeje Formation in large round dots relative to other Bandas del Sur pyroclastics in smaller grey round dots (data taken from Bryan et al. 2002, Bryan 2006, Edgar et al. 2002, Brown and Branney 2004, Dávila-Harris 2009).

Major elements normalised to 100% in a volatile-free basis. b) Zr vs CaO diagram; b) Ba vs Sr diagram showing magma mixing trends.

Fig. 11 Selected major (SiO_2 and CaO) and trace (Sr and Zr) elements and magmatic temperatures vs stratigraphic height of the Adeje Ignimbrite.

Fig. 12 Feldspar compositions of the Adeje Formation (n=452) compared with other data from pyroclastic deposits across southern Tenerife (Bryan et al. 2002) and other phonolites, tephriphonolites and basanites elsewhere (Triebold et al., 2006).

Fig. 13 Schematic cartoon showing a summary of the eruptive history and processes involved in the Adeje eruption. a) Phase 1 marks the onset of the Adeje eruption with a Plinian column depositing ~1 m of pumice lapilli fallout up to 15 km from source. b) Phase 2 involves emplacement of pyroclastic density currents (PDC's) depositing layer B or flow-unit 1 ignimbrite. c) Phase 3 records the wake of the first pyroclastic currents and the deposition of co-ignimbrite ash and pellet fall and accretionary lapilli. d) Phase 4 contains products from the eruption climax and represents one or more PDC's depositing massive, diffuse-stratified and lithic-rich ignimbrite. It records agglomeratic lapilli-tuff and widely emplaced lithic breccias suggesting vent erosion or caldera collapse.