Counting currents: resolving contradictory records of eruption history created by unsteady pyroclastic density current dynamics

Natasha J. Dowey (née Smith)*1, Richard J. Brown2 and B. Peter Kokelaar3
[1] Geography, Environment and Planning, Sheffield Hallam University, Sheffield, UK
[2] Department of Earth Sciences, Durham University, Durham, UK
[3]Department of Earth Sciences, Durham University, Durham, UK
[*] N.Dowey@shu.ac.uk [corresponding author]

This is a non-peer reviewed preprint submitted to EarthArxiv.
Feel free to contact the lead author, we welcome your feedback.

Counting currents: resolving contradictory records of eruption history created by unsteady pyroclastic density current dynamics

Natasha J. Dowey (née Smith)*1, Richard J. Brown2 and B. Peter Kokelaar3
[1] Geography, Environment and Planning, Sheffield Hallam University, Sheffield, UK
[2] Department of Earth Sciences, Durham University, Durham, UK
[3]Department of Earth Sciences, Durham University, Durham, UK
[*] N.Dowey@shu.ac.uk [corresponding author]
ORCiD (NJD): 0000-0002-9231-4781
ORCiD (RJB): 0000-0002-7415-9490
ORCiD (BPK): 0000-0002-2452-703X
Keywords: Stratigraphy; Correlation; Volcanic Hazard; Unsteadiness; Uncertainty; Volcanology

Abstract

Ignimbrite lithofacies analysis can be used to interpret the number and behaviour of pyroclastic density currents (PDCs) generated during a Plinian eruption, through identification of flow units in the rock record. However, pyroclastic stratigraphic successions are rarely complete and without breaks around a volcano, complicating regional analysis of hiatus markers. This study uses entrachron correlation to reconcile conflicting proximal and distal lithofacies architecture of the 273 ka Poris Formation, Tenerife, to reveal a coherent eruption history. The novel correlation illustrates that hiatus in PDC activity can vary spatially and rapidly due to regional-scale unsteadiness and non-uniformity in PDC dynamics. Distal stratigraphy may not accurately record the number of PDCs generated during an eruption and breaks in ignimbrite deposition do not necessarily imply discontinuous PDC development. These findings bear importantly on hazard inferences derived from ignimbrite lithofacies successions, and have significance for numerical and experimental modelling of unsteadiness in granular flows.

1. Introduction

Pyroclastic density currents (PDCs) generated during explosive volcanic eruptions are flows of volcanic ash, gas and rock that can reach internal temperatures of >500°C, travel at speeds of >200 ms^{-1} and cover vast areas (e.g., Fisher, 1966; Sparks, 1976; Fisher & Schmincke, 1984; Wilson, 1985; Branney & Kokelaar, 1992, 2002; Druitt, 1998; Sulpizio et al., 2014; Dufek et al., 2015; Lube et al., 2020). In their wake they leave complex deposits on the ground, here referred to as ignimbrites. During Plinian eruptions, ignimbrite sheets may build up, composed of several ignimbrite units interbedded with pumice or ash fall deposits (e.g., Pittari et al., 2006; Dávila Harris et al., 2013; Cavazos-Álvarez & Carrasco-Núñez, 2020). Interpretation of ignimbrite stratigraphy has been crucial in developing understanding of how these deadly hazards behave in time and space, and in unpicking eruption histories of the events that generate them (e.g., Cas & Wright, 1987; Fisher et al., 1993; Branney & Kokelaar, 1997; Lube et al., 2007; Silva Parejas et al., 2010; Williams et al., 2014).

Although a critical tool, ignimbrite analysis is not straightforward. Pyroclastic stratigraphy is rarely complete; proximal exposures may be missing or obscured due to destruction during caldera collapse (e.g., Gooday et al., 2018), bypass may lead to non-deposition (e.g., Brown & Branney, 2004), changes in eruption conditions may lead to syn-eruption scour and erosion (e.g., Gase et al., 2017), syn-eruption reworking may influence stratigraphic architecture (e.g., Wilson & Hildreth, 1998; Myers et al., 2016), and post-eruption erosion may lead to disconnected outcrops (Mues-Schumacher & Schumacher, 1996). Furthermore, Plinian eruptions are complex; different processes may be operating at different distances from the vent (e.g., Houghton et al., 2004), and pyroclastic density currents are inherently unsteady and non-uniform in time and space (Branney & Kokelaar, 2002). Stratigraphic clues may seem contradictory at different locations around the volcano unless a full enough record is present to bring together a coherent story (Fig. 1). Such factors can lead to uncertainty in our interpretations of how many PDCs were formed during an eruption, how far each travelled, their internal dynamics, and how they interacted with the environment, impacting our ability to confidently interpret eruption histories and understand future potential hazard.

This study explores how our interpretation of the number of PDCs generated during an eruption, as recorded by stratigraphic 'flow units', can be shaped by outcrop location and internal PDC dynamics. We correlate well-documented proximal (N. Smith & Kokelaar, 2013) and distal (Brown & Branney, 2004b, 2013) stratigraphic counterparts of the 273 ka Poris ignimbrite of Tenerife to interrogate factors influencing contradictory equivalent stratigraphy. We then discuss the implications of this work for uncertainty in field interpretations of ignimbrite successions and volcanic hazard analysis.

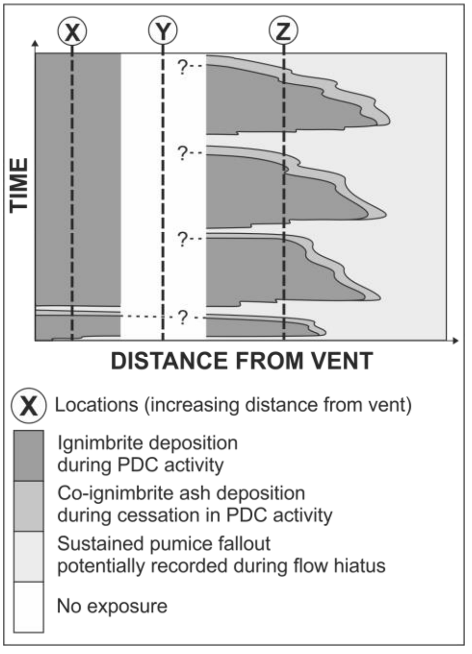

Figure 1: Schematic showing how flow units could be interpreted differently at different locations from the vent, dependent on the nature of preserved ignimbrite stratigraphy. At location X, two flow units are recorded. At location Z, four flow units are recorded. At location Y, there is no exposure, complicating correlation of flow units. Adapted after Branney and Kokelaar (2002).

1.1 Flow units and episodes of PDC hiatus

A 'flow unit' in ignimbrite stratigraphy is most simply defined as a stratigraphic package that records the passage of a single pyroclastic density current (Sparks, 1976). The term has been used for many years (e.g., Ross & Smith, 1961), although how we identify and define flow units has evolved through time.

In 1973, Sparks et al. proposed a "standard ignimbrite flow unit" paradigm, where changes in bedding, grading and pumice concentration were used to distinguish the deposits of discrete pyroclastic currents that came to a halt en masse (Sparks et al., 1973; Sparks, 1976). It is now understood that PDCs aggrade progressively from the flow boundary zone, which includes the lowermost part of the current and the uppermost part of the forming deposit (Fisher, 1966; Branney & Kokelaar, 2002). In this progressive aggradation model, a flow unit can comprise a wide spectrum of stratigraphic bedforms. Bedding and grading changes within an ignimbrite reflect the unsteadiness of PDC conditions through time, recording changes in conditions at the flow boundary zone (Branney & Kokelaar, 2002). Flow units may be recognised by well-defined upper and lower boundaries or may contain distinctive assemblages of clasts (as in Silva Parejas et al., 2010), but evidence of clear hiatus in current activity, rather than a particular stratigraphic sequence, is key in delineating flow units and discrete density current events.

Plinian fallout layers, evidence of secondary reworking or soil within an ignimbrite sequence may all provide robust evidence for a hiatus in PDC activity (e.g. Cavazos-Álvarez & Carrasco-Núñez, 2020). Ash layers correlated across large distances within ignimbrite successions can also record episodes of hiatus, where deposition of co-ignimbrite ash occurs after passage of a pyroclastic density current (e.g., Sparks & Walker, 1977; Sigurdsson & Carey, 1989; Brown & Branney, 2004b; Pittari et al., 2006). It is important to distinguish between no current activity at all, and temporarily redirected current activity that would form a local hiatus. A hiatus in one place could reflect momentary lateral redirection of a current owing to rapid changes at the vent, changes in PDC dynamics and run out distance, or topographic effects; factors we will discuss below.

1.2 Correlating ignimbrite lithofacies

To fully understand the evolution of PDC behaviour in time and space, and to correlate episodes of hiatus and therefore flow units within a single eruption, a time-geometry framework is required (Branney & Kokelaar, 2002). The deposition of lithofacies and compositional zones across an ignimbrite extent may be diachronous (e.g., Wilson & Hildreth, 1997) and physical similarities between ignimbrite lithofacies are unlikely to represent temporal correlation; lithostratigraphy does not necessarily equate to chronostratigraphy. In compositionally zoned ignimbrite sheets that record systematic changes in magma chemistry through time, geochemical correlation is an important correlative tool in revealing spatial and temporal variations in PDC behaviour (e.g., Fierstein & Wilson, 2005; Williams et al., 2014). But in ignimbrites that lack high-resolution geochemical variation, other methods are needed. Branney and Kokelaar (2002) introduced the term ‘depochron’ for a notional surface within an ignimbrite sheet connecting clasts deposited from the current at the same moment in time. However over large distances, with a lack of connecting exposure and significant changes in outcrop appearance, depochrons can be difficult to establish. ‘Entrachrons’ are notional surfaces connecting the lowermost clasts that were *entrained into the current* together at the same instant in time; they may be marked, for example, by the first appearance of a new type of pumice or lithic clast within the stratigraphy (Branney and Kokelaar, 2002). Such entrachrons need not occur in the same lithofacies in different areas (this would depend on the conditions of the flow boundary zone of the PDC at each location). In this study, we use entrachron analysis to aid correlation of distinct ignimbrite lithofacies and flow units.

2. Case study: the 273 ka Poris ignimbrite, Tenerife

2.1 Geological setting

Tenerife is a large shield volcano, with diverse volcanic products recording the interspersed remnants of basaltic shield volcanism from three volcanic rift zones (~12 Ma – 3 Ma), central pyroclastic activity (~3 Ma – 0.7 Ma), and monogenetic flank volcanoes and tuff rings (Ancochea et al., 1990, 1999; Martí et al., 1994; Bryan et al., 1998, 2000; Brown et al., 2003; Edgar et al., 2007; Cas et al., 2022; Dávila Harris et al., 2023).

The centre of the island is dominated by Las Cañadas depression (Fig. 2), which contains the present-day Teide-Pico Viejo stratovolcano and is partly encircled by a ~27 km-long wall comprising strata representing 3 Ma of volcanic activity (Martí et al., 1994; Martí, 2019). These strata become successively younger from the western Ucanca sector, through the central Guajara sector, to the eastern Diego Hernandez (DH) wall. The DH wall is the "proximal" area of this study. It is ~1.9 km long and 180–240 m high, orientated N–SSW, and exposes proximal ignimbrite deposits intercalated with lava flows, scoria cones and sedimentary strata. These deposits occur within a palaeovalley (Marti et al., 1990) bounded by the Risco Verde escarpment to the south and monogenetic scoria cones and lavas of the Cordillera Dorsal to the north. Bedding within the upper pyroclastics dips consistently at ~2° ESE, indicating that the lava substrate had a low topographic profile. Within approximately 3 km of the wall, the topography of the volcano consists of steep flanks up to 10-20°. This medial zone contains hardly any ignimbrite exposure.

In this study, the "distal" Bandas del Sur region refers to an 180° sector of the southern flanks of the volcano, stretching from the Güimar valley to Los Cristianos (Fig. 2). This region is broadly concave, extending from the steep medial flanks to lower gradient (6°) coastal flanks that reach ~5 km inland and range from 15-20 km wide. Extensive ignimbrite deposits across this part of the island record at least twelve inferred caldera-forming events, indicating that multiple stratovolcanoes have been constructed and destroyed during the island's history (Bryan et al., 1998, 2000; Brown et al., 2003; Edgar et al., 2007; Dávila Harris et al., 2023). The Bandas del Sur has a semi-arid climate prone to flash floods, and the slopes of the volcano are incised with a network of deep radial valleys. Palaeotopography indicates that the region has had a similar topography for the past 2 Ma (Pittari et al., 2006).

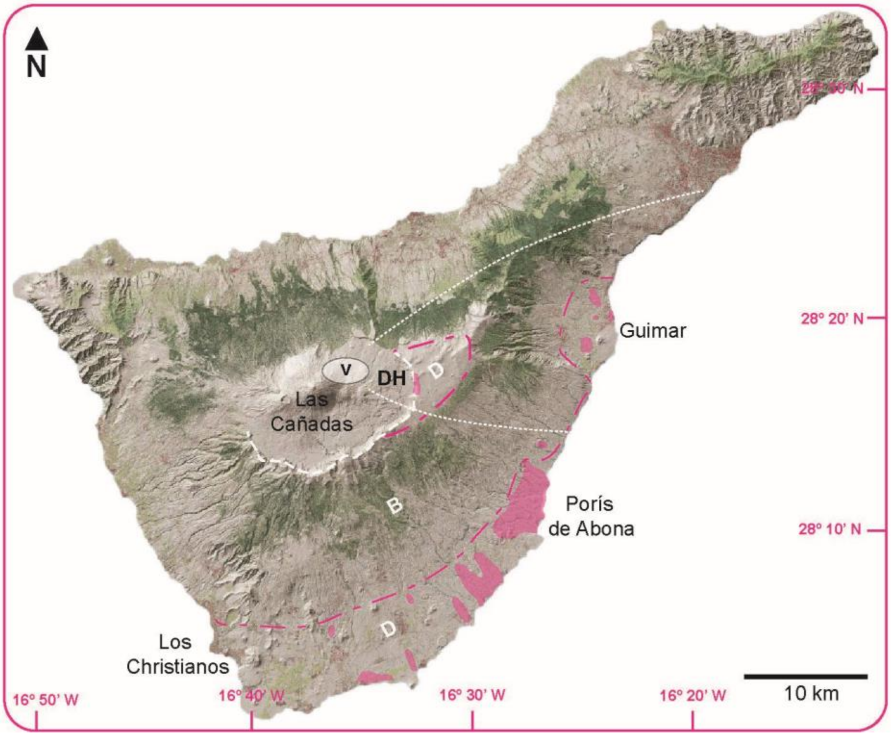

Figure 2: Map of outcrops of Poris ignimbrite (pink). Pink dashed line separates zones of deposition (D) and bypassing (B) (Brown and Branney, 2013). V = vent from Edgar et al., (2004). White dotted line is 50 cm Poris isopach from Edgar et al., (2004). DH = Diego Hernandez.

2.2 The contrasting records of the 273 ka Poris Ignimbrite

The 273 ka Poris event is one of the largest Quaternary Plinian eruptions recorded on Tenerife (Brown et al., 2003; Edgar et al., 2007). The eruption impacted >600 km^2 of the island, emplacing an ignimbrite sheet up to 40 m thick, and culminated in caldera collapse within Las Cañadas. The Poris ignimbrite succession, comprising layers of lapilli tuff, lithic breccia, ash and pumice fall layers, is exposed and well documented in the Diego Hernandez wall (N. Smith & Kokelaar, 2013) and across the Bandas del Sur (Edgar et al., 2002; Brown & Branney, 2004b, 2013).

Work by Smith and Kokelaar (2013) and Brown and Branney (2004b) applies the same lithofacies architectural approach to the analysis of proximal and distal Poris deposits (respectively; summarised in figures 3 and 4). The studies report different proximal and distal lithofacies, with apparently contradictory records of hiatus and therefore different numbers of flow units. There are no reported medial exposures to connect these distinct proximal and distal records, therefore the Poris provides a novel opportunity to examine lithofacies and flow unit correlation for a major Plinian eruption event and consider its implications.

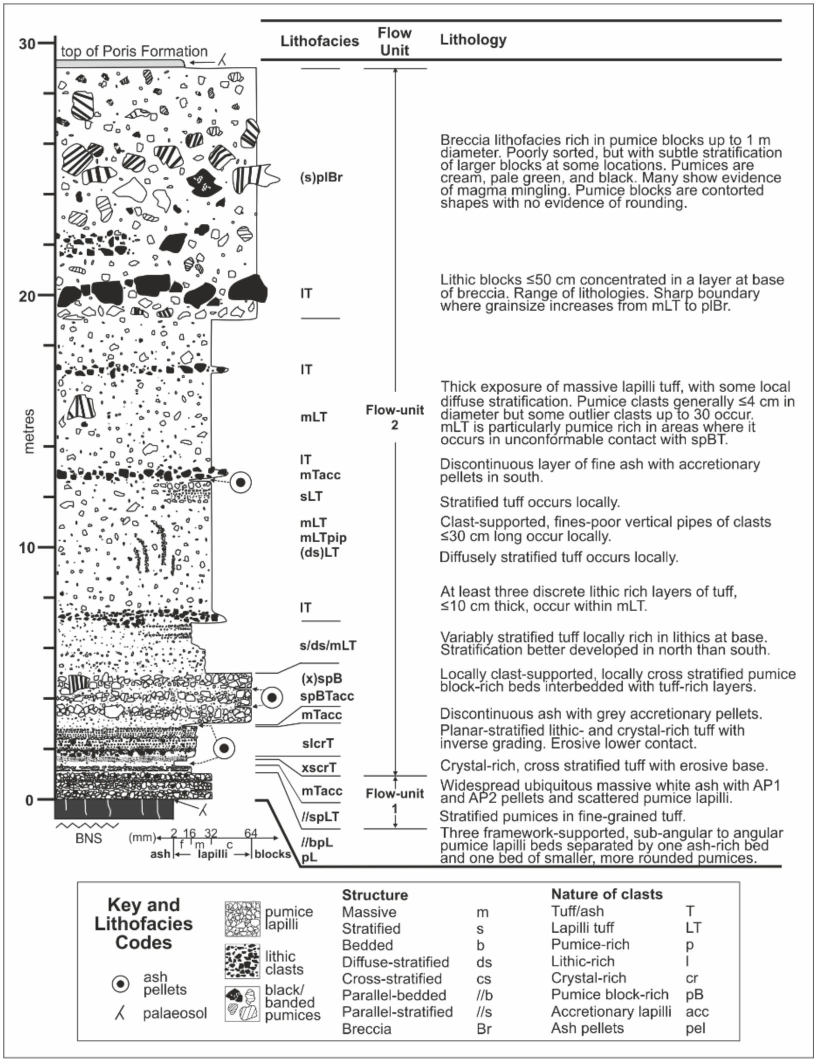

Figure 3. General vertical section of the proximal Poris ignimbrite succession (reproduced from Smith and Kokelaar, 2013). Legend is relevant for all logs presented within this work. For full description of lithocodes, see Brown and Branney (2004b).

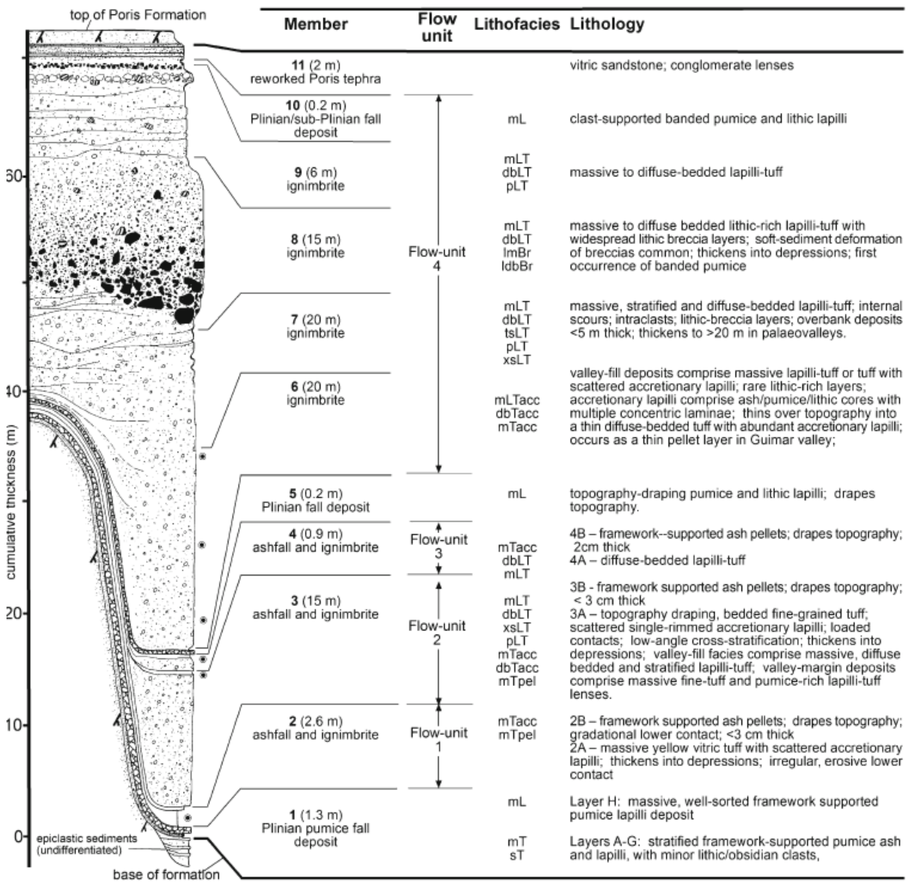

Figure 4: General vertical section of the distal Poris ignimbrite succession (reproduced from Brown and Branney, 2013). Note difference in vertical scale between Figures 3 and 4. For legend, see Figure 3.

3. Methodology

3.1 Stratigraphic analysis

This study provides a new correlation of proximal (detailed in Smith & Kokelaar, 2013) and distal (detailed in Brown & Branney, 2004b, 2013; Edgar et al., 2002) sequences of Poris pyroclastic stratigraphic architecture, through entrachron analysis, comparison of lithofacies and evidence of hiatus. In the Poris succession, the occurrence of Plinian units and co-ignimbrite ash fall layers are evidence of cessation in PDC activity, while entrachrons include the appearance of pumice and lithic clasts with distinctive colours and compositions.

Terminology

The term 'lithofacies' is used within this study to refer to a part of an ignimbrite that has distinct physical characteristics (after Branney and Kokelaar, 2002). 'Architecture' is the overall structure of the ignimbrite and how the lithofacies are arranged. Each non-genetic lithofacies name is attributed based upon these characteristics (see Figs 3 and 4). The term ignimbrite 'veneer' is used as a non-genetic description for thin ignimbrite deposits on topographic highs. The grain-size system used on stratigraphic logs is that developed by Cas et al., (2008) for volcanic nomenclature. The terms "proximal" and "distal" denote the present Diego Hernandez caldera sector (likely within 4 km of the original Poris vent) and the Bandas del Sur coastal zone respectively. Ash aggregates within ignimbrite stratigraphy are characterised using the framework provided in Brown et al. (2012); AP1 aggregates are poorly constructed, fragile ash pellets, whereas AP2 are subspherical accretionary pellets typically with an ash core surrounded by a rim of multiple concentric laminae.

3.2 Geochemical analysis

A small-scale analytical study of Poris pumices from the Diego Hernandez wall and the coastal Bandas del Sur zone was undertaken as part of this study to verify stratigraphic correlation and confirm that proximal and distal successions studied are indeed counterparts. Pumice sampling was carried out during NJD's PhD thesis (N. Smith, 2012) in 2009, and samples were geochemically analysed using X-Ray Fluorescence and Electron Microprobe analysis facilities at Leicester University in 2010. XRF was chosen in preference to single-grain tephra analysis methods to allow data to be compared with previous XRF studies of Tenerife ignimbrites (Brown, 2001; Edgar et al., 2002). Proximal Diego Hernandez samples were collected from the Cerrillar Gully and log locations 5, 10, 11, 13, 16 and 17 of Smith and Kokelaar (2013). Distal Bandas del Sur samples were collected from the Poris Quarry, Güimar Road, Tajao Road and Spooky Dog locations reported in Brown (2001), Brown et al. (2003) and Brown and Branney (2004b). Pumice samples were predominantly cream in colour, but also included black, green and mingled types. A full sample list and analytical methods can be found in Supplementary Material.

4. Proof of Poris

Stratigraphic and geochemical evidence confirms that proximal and distal exposures correlated in this study are counterparts of the Poris eruption. These outcrops have been put in stratigraphic context by previous studies (Brown et al., 2003; Edgar et al., 2007), and have been geochemically analysed by Brown (2001), Edgar et al., (2002) and others (e.g. Edgar et al., 2007). When existing data are plotted together with the new data from this study on a Zr-Nb covariation plot, proximal and distal samples show clear overlap (see Fig. 5). Furthermore, an ignimbrite overlying a paleosol on top of proximal Poris deposits sampled during this work was found to be a geochemical match to the 221 ka La Caleta ignimbrite (based on data fields from Edgar et al., 2007; see Fig. 5). The La Caleta eruption followed the 273 ka Poris event (Brown et al. 2003).

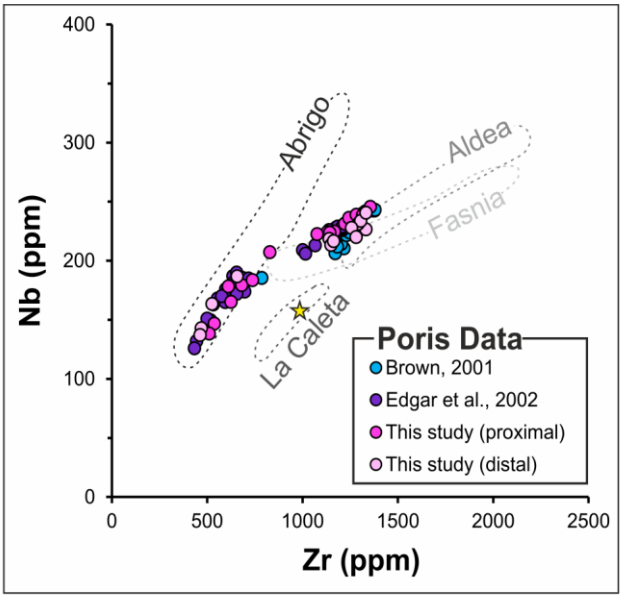

Figure 5: Geochemical correlation showing Poris data from this study and two previous geochemical studies (Brown, 2001 and Edgar et al., 2002). Stippled outlines show data fields for other ignimbrite formations of the Diego Hernandez episode of Tenerife volcanism for comparison (from Edgar et al., 2002). Star marks composition of proximal La Caleta sample. Note the two distinct data fields of the Poris eruption, highlighting the bimodal composition with more felsic and mafic compositions.

5. Using entrachron analysis to correlate contradictory eruption history

In this section physical characteristics of proximal and distal Poris deposits are summarised (detailed observations and interpretations are within Smith and Kokelaar (2013) and Brown and Branney (2004b, 2013) respectively) and a new stratigraphic correlation and reconciled interpretation is presented (see Table 1). Descriptions of distal Poris stratigraphy by Edgar et al. (2002) using a different lithofacies system are not covered in detail below, but have been considered and are reconciled with correlations presented here in Table 1. For ease of reading, interpretations are presented alongside correlations, and discussed more fully in the next section.

In this work, we interpret flow units by evidence of hiatus rather than by changes in grading or bedding patterns. Where present, diffuse bedding, grading and discontinuous scour are interpreted as evidence of progressive aggradation from a sustained PDC that experienced changing conditions at the flow boundary zone, rather than evidence of multiple PDC events (Branney and Kokelaar, 2002. However, evidence from the Poris succession illustrates how such changes at the flow boundary zone through time (unsteadiness) and in space (nonuniformity) can be *linked* to PDC runout distance and hiatus, which we consider further in the Discussion.

5.1 Phase 1: Plinian activity and ash fall (entrachon A)

Proximal record

A parallel-bedded pumice lapilli facies overlies pre-Poris lavas across the proximal Diego Hernandez wall, ranging from 10 cm – 1 m in thickness. Three layers of angular, framework-supported pumice lapilli occur separated by an ash bed and a bed of rounded, smaller pumices. The unit contains abundant dark green obsidian fragments.

Distal record

The distal Plinian deposit consists of distinct beds of framework-supported pumice (B, D, E, G and H) interspersed with ash layers (A, C and F). The pumice beds have different geographic distributions; lower beds (B, D, E) are exposed between Fasnia and Aldea Blanca. Bed H is notably coarser and is thickest at Güimar in the east. Green obsidian chips are markedly concentrated at the base of an exposure near Tajao.

Correlation

Distinctive green obsidian chips are found in both proximal and distal bedded Plinian material and form the first correlative entrachron of the Poris succession, indicating that both proximal and distal material was created during the same phase of Plinian activity (Fig. 6).

These lithofacies are similar in proximal and distal zones, with ash layers recognised between fallout layers distally, and finer beds also interspersed in proximal fallout facies. However, they are not exactly equivalent and may not be temporal correlatives.

Phase	Proximal record summary[1]	Distal record correlatives[2,3,4]	Entrachrons and rationale for correlation
8. Cessation of PDC activity and fallout	Plinian fallout is not recorded proximally; pumice-rich gravels and soil overlay the stratifed pumice block breccia.	Member 10 Plinian/sub-Plinian fall deposit[2] [Uppermost part of Guimar Member[3]; Units F and G[4]]. Overlain by reworked material.	Distal fallout has no proximal counterpart, although may temporally correlate with upper parts of stratified pumice block breccia.
7. Waning PDC activity	Stratified pumice block breccia rich in black and banded pumices.	Member 9 ignimbrite[2] [Guimar[3]; Mareta[4]]	Characteristics of both proximal and distal lithofacies are interpreted to indicate waning processes.
6. Peak intensity and caldera collapse	Lithic block layer and increased occurrence of black, green and banded pumice. Matrix colour change from cream to pinkish beige.	Member 8 lithic-rich ignimbrite, with first distal occurence of black and banded pumices [2] [Tamadaya[2]; Quinta[3]]	**Entrachron D: Increased lithic block entrachron.** **Entrachron E: Black and banded pumice entrachron.** Pink matrix colour noted in both proximal and distal facies.
5. Unsteady waxing PDC activity with scour and bypass	Stratified to diffusely-stratified tuff overlain by massive lapilli tuff containing distinct lithic-rich layers.	Members 6 and 7 ignimbrite[2] [Rio and underlying Jurado[3]; Upper part of Abona[4]]. *DISTAL PDC HIATUS*	Proximal stratified facies are interpreted as deposits of a non-uniform, unsteady current, as is the Jurado[3]. Upper part of Abona[4] reported to contains subunits bounded by lithic breccia layers, similar to proximal facies. Evidence of scour and bypass occurs in both proximal and distal lithofacies.
4. Simultaneous Plinian and PDC activity, with period of distal PDC hiatus	Locally framework-supported, cross stratified pumice block facies containing AP2 accretionary pellets and green pumices.	Member 4 ashfall and ignimbrite[2], Member 5 Plinian fall deposit[2] [Cueva Honda ignimbrite, Caballos fallout[3]; Unit D fallout overlain by Unit E 'surge'[4]] *DISTAL PDC HIATUS*	**Entrachron C: Pale green pumices.** Proximal facies is a unique to proximal area, exhibiting evidence of deposition by both fall and flow processes[6]. Distinct pale green pumices occur in both proximal facies and distal fallout.
3. Phreatomagmatism and renewed PDC activity, with period of distal PDC hiatus	Cross stratified fine grained tuff overlain by distinctly grey crystal-rich planar stratified tuff. Discontinuous ash layer with grey accretionary pellets.	Member 3 ashfall and ignimbrite[2] [Magua[3]; Manteca[4]]	**Entrachron B: Grey accretionary pellets.** The grey cross- and planar-stratified tuff facies are uniquely proximal, but both proximal and distal correlatives are grey in colour, with distinctive grey accretionary pellets.
WIDESPREAD PDC HIATUS			
2. First density stratified PDC, followed by widespread PDC hiatus	Stratified pumices within tuff overlain by continuous, massive ash-rich tuff	Member 2 ashfall and ignimbrite[2] [Centinela[3]; Unit C 'surge'[4]]	Both proximal and distal units overlie the Plinian deposit below with no evidence of a time break. AP2[5] accretionary pellets occur in both the Centinela and proximal massive ash facies.
1. Plinian activity with ash deposition	Parallel bedded pumice lapilli facies overlying pre-Poris lavas	Member 1 Plinian fall deposit[2] [Hidalga[3]; Unit B fallout[4], Unit A ash[4]]	**Entrachron A: Green obsidian.** Green obsidian fragments occur in proximal and distal fallout. Lithofacies are physically similar in proximal and distal zones.

Table 1: Summary of the stratigraphic correlation between proximal and distal Poris lithofacies presented in this paper. Superscript indicates references (1: Smith and Kokelaar, 2013; 2: Brown and Branney, 2013; 3: Brown and Branney, 2004b; 4: Edgar et al. 2002; 5: Brown and Branney, 2012; 6: Dowey and Williams, 2022).

Interpretation

The Poris eruption began with formation of a dilute ash cloud, deposition from which is recorded in the southeast of the island. A Plinian plume developed and pumice deposition commenced, along with lithic material derived from an obsidian-rich vent zone. The concentration of obsidian chips at the base of the deposit at Tajao could reflect subtle differences in terminal fall velocity between pumice and lithic clasts.

The deposition of ash records temporary hiatus in Plinian activity, which may reflect unsteadiness in the Plinian column at source, and/or may have been localised due to changes in wind direction. A subrounded pumice bed in the proximal zone indicates dilute pyroclastic current activity or wind action, at least proximally, sufficient to rework Plinian material. The distal record indicates that Plinian dispersal gradually shifted from southeasterly to easterly. There is no proximal physical equivalent of the coarser pumice facies observed at Güimar, although the upper part of the proximal Plinian unit is interpreted to have been reworked during phase 2 (see below), therefore any equivalent material may have been removed.

Figure 6. Dark green obsidian lithics are abundant in proximal and distal exposures of Poris Plinian fallout. Photo taken at location in the DH caldera wall at 28.280273°N, 16.549526°W

5.2 Phase 2: First density stratified PDC activity and widespread hiatus

Proximal record

Stratified layers of Plinian-population pumices, and smaller, rounded pumices, within tuff are in erosional contact with the Plinian deposit. This facies is overlain by a continuous, massive ash-rich tuff, <200 mm thick, containing both AP1 unstructured ash pellets and AP2 accretionary pellets ≤20 mm in an ash-rich matrix with scattered subangular Plinian-population pumice lapilli.

Distal record

A massive, fine-grained vitric tuff containing AP2 accretionary lapilli and Plinian population pumices occurs above the distal Plinian unit. This tuff has an erosive lower contact and thickens into depressions, and is overlain by a layer of framework supported AP1 pellets (≤15 mm in diameter) that drapes topography.

Correlation

Both proximal and distal lithofacies in this part of the succession record the onset of PDC activity, but have different characteristics. Distally there are no stratified pumice lithofacies. Proximally there are no framework-supported pellet facies. Correlation is inferred through location-based interpretation of these lithofacies.

Interpretation

A pyroclastic density current was generated by fountaining of the eruption column following widening of the obsidian-rich vent. At first, only dilute upper parts were able to surmount the caldera topography in the DH sector of the proximal zone, where it was able to roll, saltate and rework Plinian pumice lapilli from the underlying substrate to created stratified layers of pumice within tuff (Fig. 7). However, where this density-stratified PDC was able to reach the coastal zone, potentially coevally through topographic lows in the wall, it deposited valley-fill tuff in topographic lows and veneers on topographic highs. Multi-rimmed AP2 ash aggregates that formed in the density current were deposited along with ignimbrite (Brown et al. 2010). This is the first of three valley fill and veneer ignimbrites recognised in the distal Poris succession.

The widespread ash-aggregate-rich layer found both proximally and distally is interpreted to record a widespread hiatus in PDC activity that allowed for deposition and preservation of unstructured ash pellets. Proximally, multi-rimmed accretionary pellets became deposited along with unstructured ash pellets in an ash-laden near-plume environment (see discussion). Distally, a layer of clast-supported AP1 pellets formed by fallout from the co-ignimbrite cloud.

Figure 7. Evidence of widespread hiatus is registered by massive ash facies with accretionary lapilli in the DH wall, and widespread ash pellet layer distally.

5.3 Phase 3: Phreatomagmatism and PDC activity (entrachron B)

Proximal record

Proximally, the aggregate-rich ash is overlain by a thin cross-stratified, fine-grained tuff with an erosive base, which is overlain and scoured into by a distinctly grey, stratified tuff rich in small crystals and altered lithics (including plutonics), with variable stacked layers of inversely graded pumices. In two northern exposures this facies is capped by an ash layer containing distinctive small accretionary pellets (<1 cm) with grey cores and less brittle rims than in the facies below. In central and southern exposures the grey lithic- and crystal-rich stratified unit has a gradational contact with the facies above and the pellet layer is absent.

Distal record

In the distal stratigraphic sequence, the phase 2 ash pellet layer is overlain by a second valley fill and veneer ignimbrite; a grey, massive, AP2 accretionary lapilli-bearing tuff that thickens in depressions and shows complete gradation to veneer facies on steep slopes and paleohighs. This is capped by a second thin AP1 ash pellet layer that is extensive across the distal region. A third veneer and valley-fill ignimbrite overlies this, outcropping between La Caleta and Montana Magua, capped by a third AP1 ash pellet layer. In this facies, ash pellets exhibit distinct grey cores.

Correlation

The lithic-rich, grey, cross stratified and planar stratified tuff facies are uniquely proximal lithofacies; no reported distal lithofacies is rich in fine lithics or similarly stratified. However, the grey colour of the distal massive lapilli tuff is an indication that it may be a distal counterpart. The small, grey accretionary pellets observed proximally and distally (Fig 8) are interpreted here as a distinctive entrachron and are the basis for correlation of these facies.

Interpretation

Very fine fragmentation of lithics in the proximal facies is interpreted here as a proximal record of heightened explosivity, recording a period of phreatomagmatism. This unit has characteristics similar to phreatomagmatic ignimbrites at Somma-Vesuvius, and contains altered plutonics that may indicate a period of interaction with a hydrothermal system at depth (Barberi et al., 1989; Cioni et al., 1999).

Lithic material from the conduit and vent zone became finely fragmented and entered a pyroclastic density current. PDC activity was at first energetic and erosive, and potentially led to bypass to distal zones. In the proximal region, the PDC was rich in fine lithics, creating distinct lithofacies, but by the time it reached the distal flanks it had shed much of its lithic load and deposited more typical massive lapilli tuff. On distal topographic highs between barrancos, ignimbrite veneer was deposited.

Unsteady waning of PDC activity then occurred, recorded in stacks of stratified and graded pumices (Fig. 9) proximally. Local hiatus at the northern edge of the Diego Hernandez paleovalley allowed ash pellets to be locally deposited while deposition continued elsewhere along the wall. Unsteady waning led to changes in PDC run-out distance and episodes of distal hiatus, during which deposition of ash pellets from a co-ignimbrite cloud occurred.

Phreatomagmatism may have contributed to the different style of ash aggregate observed during phase 3. Highly fragmented fine-grained lithic material entered the plume as a grey ash, and ash aggregates containing grey ash cores formed. The irregular, contorted nature of the accretionary pellets at this stage, compared to those elsewhere in proximal stratigraphy, may indicate that the pellets underwent less 'baking' within the plume and/or PDC. Conceivably, phreatomagmatic conditions may have caused a drop in temperature of the erupted material, contributing to this effect.

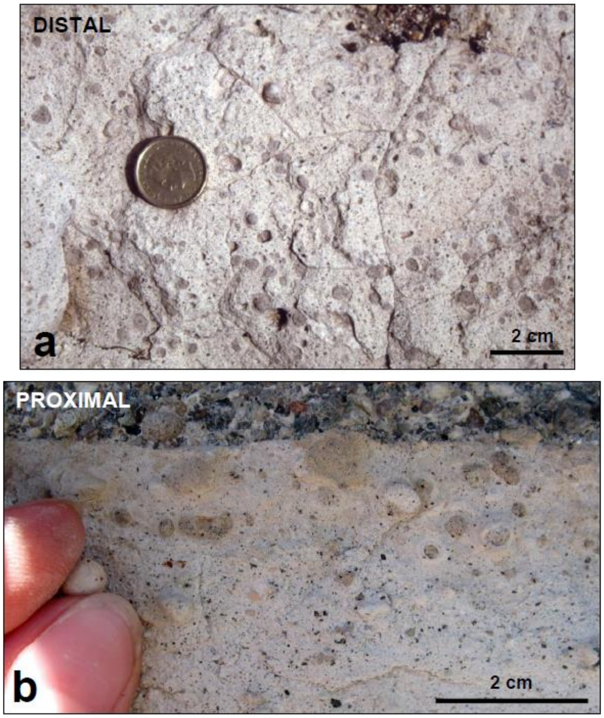

Figure 8: The grey ash pellet entrachron, evidenced in both the proximal (28.280273°N, 16.549526°W) and distal (Tajao Road locality) region.

Figure 9: Repeating stacks of inversely graded pumices deposited during episode of PDC waning in the proximal zone 28.280273°N, 16.549526°W

5.4. Phase 4: Simultaneous Plinian and PDC activity (entrachron C)

Proximal record

A locally framework-supported, cross stratified pumice-block facies containing AP2 accretionary pellets overlies the grey lithic stratified facies in the DH wall. Pumice blocks up to 300 mm diameter occur and contain mafic blebs. Larger pumices are distinctly pale green in colour. Fines-rich layers separate pumice-rich beds, with evidence of internal scour. Low-angle cross-stratification occurs and pumice beds pinch out across exposures. AP2 accretionary pellets occur and are brittle, relatively large (<20 mm), with white cores.

Distal record

The third distal ash pellet layer is stratigraphically overlain by a topography-draping layer of framework-supported pale green pumice lapilli. It occurs between La Caleta and El Baul and approaches 120 mm thick in Güimar, but is only one clast thick southwest of Poris de Abona. This is the second Plinian fallout unit recorded distally.

Correlation

The proximal cross stratified pumice block lithofacies is another exclusively proximal lithofacies. It exhibits evidence of deposition by both fallout and flow processes (Dowey & Williams, 2022), and contains zones of angular, framework-supported pumices that share characteristics with the distal Plinian unit. The distinct pale green pumices present in both the proximal pumice block unit and the distal Plinian unit are interpreted here as a correlative entrachron.

Pumice samples from this stage of the eruption (taken from the proximal cross stratified pumice block lithofacies and distal second Plinian facies) both contain notably less Zr than proximal and distal samples of the initial opening Plinian event (~1200 ppm on average as opposed to ~1400 ppm respectively) (Fig 10).

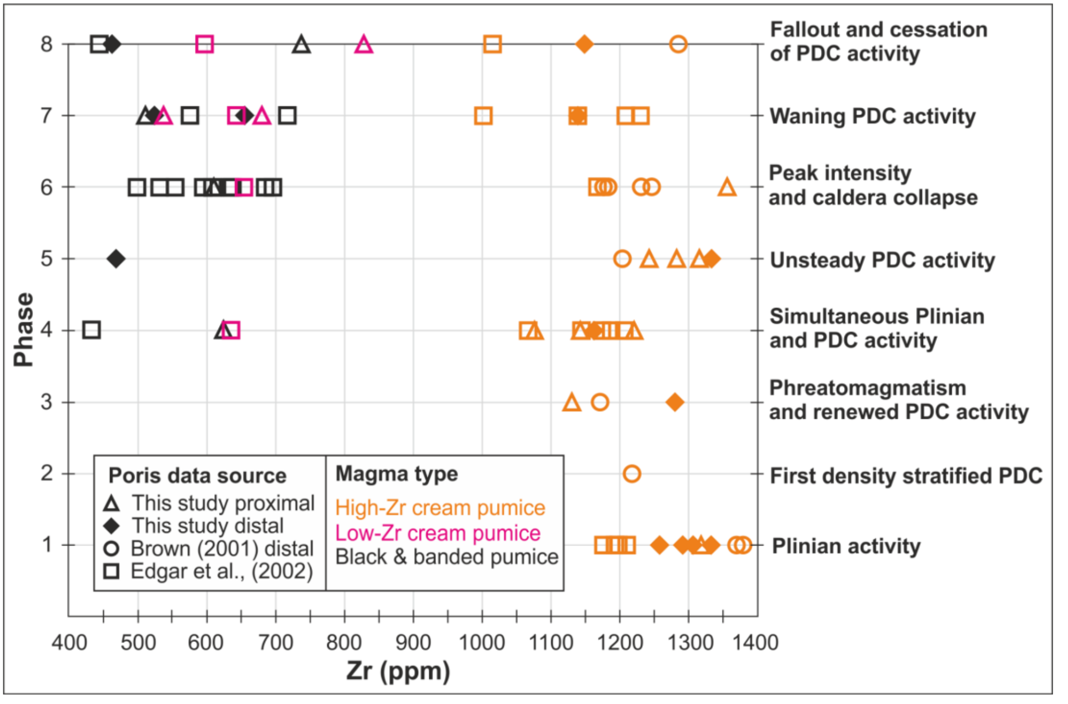

Figure 10: Zirconium concentration plotted against interpreted phase for Poris data from this study, Brown (2001) and Edgar et al., (2002). Using nomenclature and correlations summarised in Table 1, data plotted at each phase are: 1 = //bpL (this study), Unit B (Edgar), Hidalga (this study; Brown); 2 = Centinela (Brown); 3 = slcrT (this study), Magua (this study; Brown); 4 = spBT (this study), Abona (Edgar), Caballos (Brown); 5 = s-ds-mlLT (this study), mLT (this study), Jurado (Brown), Rio (this study); 6 = base of splBr (this study), Tamadaya lBr (Brown), Quinta (Edgar); 7 = splBr (this study), Tamadaya [above lBr] (this study), Mareta (Edgar); 8 = top contact of splBr (this study), Guimar (this study; Brown), Units F and G (Edgar). Note that at phase 8, waning stage fallout is the uppermost distal Poris deposit. Proximally, there is no upper fallout recorded, therefore pumice analyses from the uppermost part of splBr are plotted here for comparison.

Interpretation

Following the phreatomagmatic phase, the eruption reverted to magmatic and a Plinian column significant enough to be recognised in the rock record was established. Proximally, PDC activity did not cease and proximal coarse Plinian fallout interacted with turbulent density currents to form a novel hybrid lithofacies (Dowey & Williams, 2022). The hiatus in PDC activity across the distal region (that had allowed for deposition of the third ash pellet layer) now allowed for Plinian deposition to be recorded in the Bandas del Sur. The proximal hybrid lithofacies is therefore a time correlative to the distal Plinian unit, and possibly also to parts of overlying distal ignimbrite facies.

There is no evidence of hiatus in PDC activity in the proximal area at this time, but there is evidence that proximal density current activity was unsteady and non-uniform; stratification and fine-grained ash and crystal layers deposited between pumice block rich beds reflect changing conditions at the flow boundary zone.

The influx of pale green pumice and lower Zr bulk pumice chemistry at this stage may reflect the tapping of a different zone of the magma system during and following phreatomagmatism. A subtle change in plumbing may also account for the increased abundance of mafic blebs observed in proximal pumices at this stage.

5.5 Phase 5: Unsteady waxing PDC activity with scour and bypass

Proximal record

The proximal hybrid unit is overlain by up to 2 m of variably stratified to diffusely stratified tuff, preserved at only a few localities due to the erosive base of a more lithic-rich tuff facies above. In northern exposures this facies is in sharp contact with the hybrid facies, and contains inversely graded pumices. In central exposures it is in gradational contact with the hybrid facies below, and in southern Diego Hernandez outcrops it is in erosive contact with the hybrid facies, truncating the pumice-block beds.

Stratigraphically above, and in erosive contact with, the stratified tuff lies 10-12 m of predominantly massive lapilli tuff, containing distinct layers of lithic-rich tuff < 200 mm thick. These lithic-rich layers can be traced along the Diego Hernandez wall and are associated with load and flame structures and scour and bypass surfaces. At one location, the most southerly in the DH wall, a localised and discontinuous stratified ash layer, <50 mm thick, occurs, overlain by a lithic tuff layer. The overlying lithic-rich layer can be traced across adjacent outcrops, but the ash layer does not continue.

Distal record

A geographically-restricted valley fill ignimbrite overlies the second distal Plinian unit, consisting of massive lapilli tuff that passes into thin ignimbrite veneers. This unit occurs between La Caleta and Güimar and comprises massive lapilli tuff rich in accretionary lapilli that passes laterally into diffuse stratified veneers on paleohighs; at Güimar it is associated with an ash pellet fall layer.

This lithofacies is overlain by a far more geographically extensive member, which in paleovalleys comprises homogenous massive tuff up to 20 m thick. On paleohighs, a clear erosive surface occurs at its base. Veneer exposures include variably stratified and cross stratified tuff, with layers of lithic lapilli and blocks common. This part of the distal stratigraphy contains complex bedforms (Brown & Branney, 2004a), scours, and splay and fade stratification.

Correlation

The proximal stratified to diffuse stratified tuff facies is vertically and laterally variable, indicating that this phase began with turbulent, unsteady, non-uniform flow-boundary zone conditions (Branney and Kokelaar, 2002). The geographically restricted distal veneer and valley fill ignimbrite may be its counterpart, although there is no clear entrachron to connect the two. The widespread and thick nature of the more geographically extensive ignimbrite makes this unit a likely counterpart of the proximal thick massive lapilli tuff lithofacies; both include zones of lithic-rich tuff.

Interpretation

Sustained pyroclastic density current activity waxed in energy, but continued to be unsteady, with flow-boundary zone conditions that led to stratified lithofacies proximally. Coarse proximal fallout input to the DH sector ceased sufficiently to no longer be registered in the deposited material. PDC run out increased sufficiently to reach distal zones, at first with a minimal geographic extent. The PDC did not reach Güimar but co-ignimbrite ash deposition occurred at this location.

More significant pyroclastic density current waxing was likely then instigated by instabilities in the conduit-vent region that led to increased entrainment of lithics into the current. Proximally, waxing is marked by erosion and lithic-rich layers associated with scour. A highly localised ash bed at the southern edge of the DH wall is possibly evidence of temporary thalweg migration within the DH paleovalley at this time (see discussion). Distally, waxing is recorded in a sharp increase in the geographic extent of massive lapilli tuff at this time, with increasing lithic content. The relatively small thickness of material recorded proximally at this stage indicates bypass of pyroclastic material to the distal zone (where up to 30 m thickness of ignimbrite is recorded). Distally, regressive bedforms indicate significant bypass into the sea (Brown & Branney, 2004a).

5.6 Phase 6: Peak intensity and caldera collapse (entrachrons D and E)

Proximal record

A lithic-block layer, <1.5 m thick, occurs in the Diego Hernandez wall. Matrix-supported blocks are up to 1 m in diameter and include a wide variety of lithologies, including hydrothermally altered clasts (Fig. 11). This block layer, just one or two blocks thick, occurs between the massive lapilli tuff below and a lithofacies rich in mafic pumice blocks above. The contact with massive lapilli tuff is planar and distinct due to an increase in pumice size, an increased occurrence of black, green and banded pumice, and a matrix colour change from cream to pinkish beige.

Distal record

Distally, a massive to diffuse stratified lithic-rich lapilli tuff occurs, with widespread lithic breccia layers in tuff with a pink-weathering matrix. This facies, which is up to 15 m thick, contains the first occurrence of mafic banded pumices in the distal region. Load and flame structures involving underlying ignimbrite are common. This lithic-rich facies has a gradational contact with overlying facies.

Correlation

The increased influx of lithic material and of mafic and banded pumices at this point in the eruption mark distinctive entrachrons that enable correlation of this part of the distal sequence to the lithic block tuff layer in the DH wall

Cream pumices sampled from the matrix of the proximal lithic block layer and from the distal lithic-breccia lithofacies have Zr contents ranging from 1150-1400 ppm. The black and banded pumices samples analysed from these facies contain 500-800 ppm Zr (see Fig. 10).

Interpretation

Following the ejection of large volumes of magma during phase 5 waxing PDC activity, a critical extent of magma evacuation was reached. The ‘chamber’ roof collapsed, and large faults dilated, disrupting the surrounding hydrothermal system. Conduit-derived, hydrothermally altered lithic blocks entered the unstable eruptive jet(s) and the waxing pyroclastic density current became extremely lithic-rich.

The lower contact recording this phase is sharp in the proximal zone, whereas distally load and flame features are common. This implies that the lithic-rich PDC was highly erosional in the near-vent zone, creating a relatively planar surface, whereas distally material piled up on top of previously deposited 'fluffy' ignimbrite, and sank into it. The thin proximal lithic-block layer implies significant bypass to the distal zone, where, relatively thick lithic rich breccia is recorded.

Poris caldera collapse subtly changed the plumbing of a complicated internal system. Although available earlier in the eruption, evident in blebs and mingled ballistics in proximal Phase 4 deposits, there was a large influx of the low-Zr magma series in the closing stages of the Poris eruption. The contemporary eruption of two discrete (high-Zr and low-Zr) magmas also occurred during the Aldea, Fasnia, Caleta and Abrigo events, also recorded in the Diego Hernandez wall (Edgar et al., 2007). It has been suggested that the coexistence of two separate magma reservoirs throughout this ~300 ka period is unlikely; the persistence of the distinct magmas may instead reflect repeated melting of different protoliths, with repeated fractionation of the magmas, following the caldera collapse and structural changes associated with each major eruption (Edgar et al., 2007).

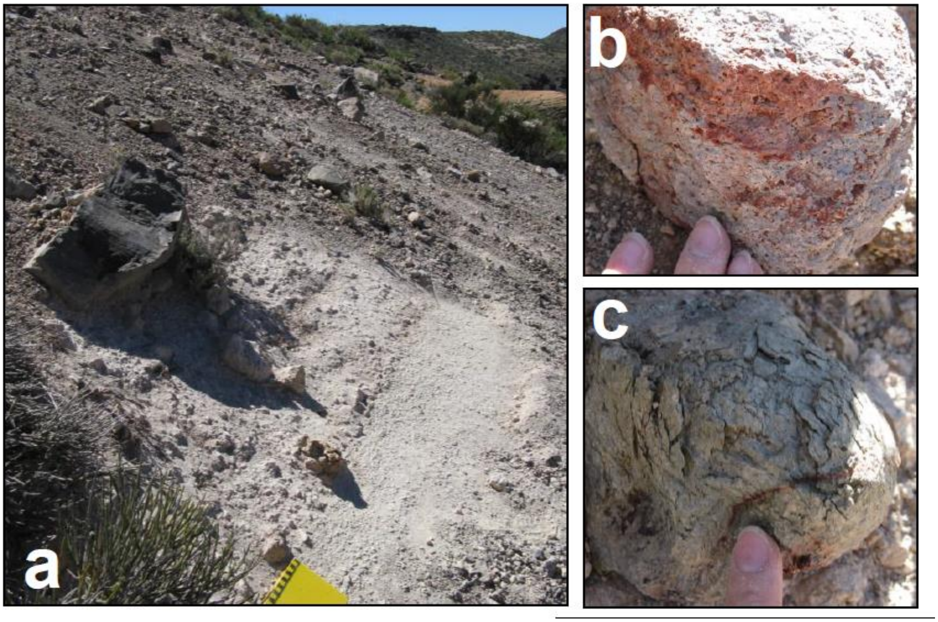

Figure 11. (a) The transition from massive lapilli tuff to the lithic block layer in the proximal Poris succession, visible when scree is brush away. Large lithic boulder projecting at angle is 40 cm across and in situ. Hydrothermally altered blocks (b) and lithics with spallation texture are observed (c).

5.7 Phase 7: Waning PDC activity

Proximal record

A poorly-exposed, 10 m thick, stratified pumice-block breccia, rich in banded and black pumice blocks ≤1.5 m in diameter, is present atop phase 6 massive lapilli tuff across the DH wall. A key exposure of this breccia occurs in a gully at Montaña El Cerrillar just north of the DH wall. Lithic clast size is similar to that seen in the Poris massive lapilli tuff. Stratification is variable and is distinguished by the changing abundance of pumice blocks; some zones have greater concentrations of large pumices whereas others are richer in lithics.

Distal record

A massive, diffuse bedded and pumice-rich lapilli-tuff facies with a relatively low lithic content overlies the distal lithic-rich breccias with a gradational contact. These facies contain both cream phonolitic and banded tephriphonolitic pumice. The lower bed comprises a thin (200–400 mm), massive layer with abundant inverse-graded pumices and normal-graded lithic lapilli in many locations. The upper part contains clast-supported. pumice-rich ignimbrite. The facies is up to 10 m thick.

Correlation

Correlation here is based upon the nature of the lithofacies, which, although very different, both indicate waning processes. Proximally, after considerable bypass during phase 6, deposition has begun again, with preservation of large pumice blocks, indicating waning. Distally, normal grading of lithic clasts and inverse grading of pumices is indicative of waning flow (Branney & Kokelaar, 2002).

The occurrence of large phonotephrite pumice blocks is striking in the proximal region, but the black/banded pumice entrachron is placed where the influx of black/banded pumice material is first recorded (at the point of the lithic block layer).

Interpretation

Following climactic explosions and caldera collapse, pyroclastic density current activity waned in energy enough for at least 10 m of material containing large pumice clasts to be deposited proximally, although runout was still sufficient to have widespread coverage of distal reaches. The similarity in thickness between the proximal and distal waning stage facies at this stage may be coincidence (the thickness removed during post-Poris reworking is unknown), but it could be an indication that aggradation was persistent in the proximal zone during this waning phase with little bypass. The lack of coarse pumice blocks in distal exposures is most likely to be due to breakage during transport across the volcanic flanks. As the PDC waned and run out distance decreased, retrogradation of the ignimbrite sheet led to a strand line of pumice rich material in the upper part of the distal ignimbrite (Brown and Branney, 2013).

5.8 Phase 8: Cessation of PDC activity and fallout

Proximal record

The stratified pumice-block breccia is the final deposit recorded proximally. In the DH wall, it is directly overlain by a soil 38 cm thick, and in the Cerrillar Gully it is overlain by 5 m of stratified pumice-rich gravels.

Distal Record

At Güimar, the uppermost distal Poris ignimbrite lithofacies is overlain by a clast-supported lithofacies comprising cream pumice lapilli overlain by banded pumice lapilli. This fallout unit is overlain by reworked Poris material.

Correlation

The distal fallout layer at Guimar has no proximal counterpart although it may temporally correlate with upper parts of the proximal stratified pumice block unit.

Interpretation

Pyroclastic current activity ceased in the distal zone and Plinian fallout tephra was deposited, recorded at Güimar. Plinian deposition may have been ongoing throughout the Poris eruption, only being recorded when currents waned sufficiently (during phase 4). Alternatively, Plinian activity may have ceased following the hybrid phase and restarted towards the end of the eruption. The lack of a proximal physical correlative to the distal fallout layer could be due to post-eruption sedimentary reworking, but it may reflect continuation of pyroclastic density current activity in the proximal zone after flow had ceased in the distal zone. As the current waned, regressive deposition of tuff may have occurred as the flow run-out distance diminished; Plinian pumices would have fallen into the current in the proximal zone and would not have been recorded as a fallout layer.

6. Synthesis

6.1 Correlating flow units to create a coherent narrative for the 273 ka Poris event

The distal Poris ignimbrite succession records four flow units, delineated by three widespread ash pellet fallout layers, providing evidence for four discrete pyroclastic density currents during the 273 ka Poris eruption. However, the proximal record contains definitive evidence for only two flow units (delineated by the phase 2 ash lithofacies). Only *local* hiatus in ignimbrite deposition is recorded subsequently in the proximal succession, in discontinuous ash beds with ash aggregates at the northern (phase 3) and southern (phase 5) edges of the Diego Hernandez wall. Entrachron analysis of the distal and proximal records indicates that many distal lithofacies have a temporal, although not always physically similar, proximal counterpart lithofacies, allowing correlations to be made between the two records and a coherent story to be developed. We propose that the documented Poris succession could have been deposited by only two, density-stratified, pyroclastic currents (Fig. 12).

Following an opening phase of Plinian fallout activity (phase 1), an initial PDC was generated but was relatively small, and was initially blocked by caldera topography proximally (phase 2). There was then a fundamental hiatus in PDC activity across proximal and distal zones, allowing ash aggregates to be deposited proximally and the first co-ignimbrite ash pellet layer to be deposited distally.

A second PDC was generated during a phase of phreatomagmatic activity. This second current was sustained, but experienced unsteadiness through time. During periodic waning, deposition continued close to source but changes in run out distance led to two widespread hiatuses in the distal zone: the first is recognised in an ash pellet fallout layer and correlates with local hiatus proximally (phase 3); the second is recognised by an ash pellet fallout layer and overlying Plinian unit, which correlates temporally with unsteady hybrid activity proximally (phase 4).

Current activity then began to step up (phase 5), with a transition from stratified to massive lapilli tuff facies proximally, an incursion of lithic-rich layers, and an increasing geographic distribution of ignimbrite facies in distal reaches with evidence of bypass to the sea. This episode, which likely coincides with incremental destabilisation of the edifice, culminated in caldera collapse (phase 6) marked by a significant influx of both lithics and banded pumices in proximal and distal reaches, and considerable bypass of the proximal area. Following this, PDC activity began to wane, recorded in distinctly different lithofacies in proximal and distal zones (phases 7 and 8). During the final waning stage of the eruption (phase 8), the run-out distance of the density current gradually decreased and Plinian deposition was recorded in some distal zones.

6.1 Potential for additional hiatus

The potential that more hiatus episodes occurred during Poris PDC activity and were lost from the rock record by cryptic erosion must be considered. It seems unlikely that further significant hiatus would have occurred during phase 5 and 6, at a time when lithofacies indicate that PDC activity was waxing dramatically. If periodic unsteadiness of the second, sustained PDC occurred at this time, run-out distance of the current at this point was such that no further hiatuses would have been recorded in the Bandas del Sur. Although lithofacies from the earlier phases of current activity were partly removed during phase 5 erosion (see log 13 of Smith and Kokelaar, 2013), there are key exposures where gradational and non-erosive contacts between lithofacies (logs 1-5 of Smith and Kokelaar, 2013) make the likelihood of further, cryptic, hiatus during phases 1-4 seem slim.

6.2 Missing parts of the puzzle

It is important to recognise that the proximal Poris lithofacies architecture provides a local snapshot, giving insight into the processes occurring in a particular sector during the eruption. No other proximal Poris exposures have been reported, but if they did exist they may display a different set of lithofacies. Changes in dispersal direction, topography and substrate around the vent would likely contribute to complex variability in different sectors (e.g., Fierstein et al., 1997). Vent-radial and medial exposures of Poris deposits would add to the eruption history, possibly shedding more light upon the hiatus issues; but these aspects of the story remain missing.

The distal region provides a far broader realm of exposure, but only provides a record of the material that was not bypassed to the ocean. It has been suggested, based upon onshore ignimbrite deposits of eruptions from the last 600 ka, that density currents mainly moved towards the southeast of Tenerife from the central Cañadas zone (Edgar et al., 2007). However, because material bypassed into the ocean in the Bandas del Sur region, where the coastal slopes are the least steep on Tenerife, and because there are few or no deposits in steeper medial reaches above Bandas del Sur where currents must have passed, it is conceivable that pyroclastic density currents moved in other directions away from the vent, and that these are not registered in subaerial deposits because of erosion or non-deposition (Brown and Branney, 2004b). It is also possible that Poris deposits elsewhere on the island have been eroded or destroyed during subsequent structural events such as lateral collapse, giving a misleading view of PDC flow direction (e.g., Dávila Harris et al., 2011).

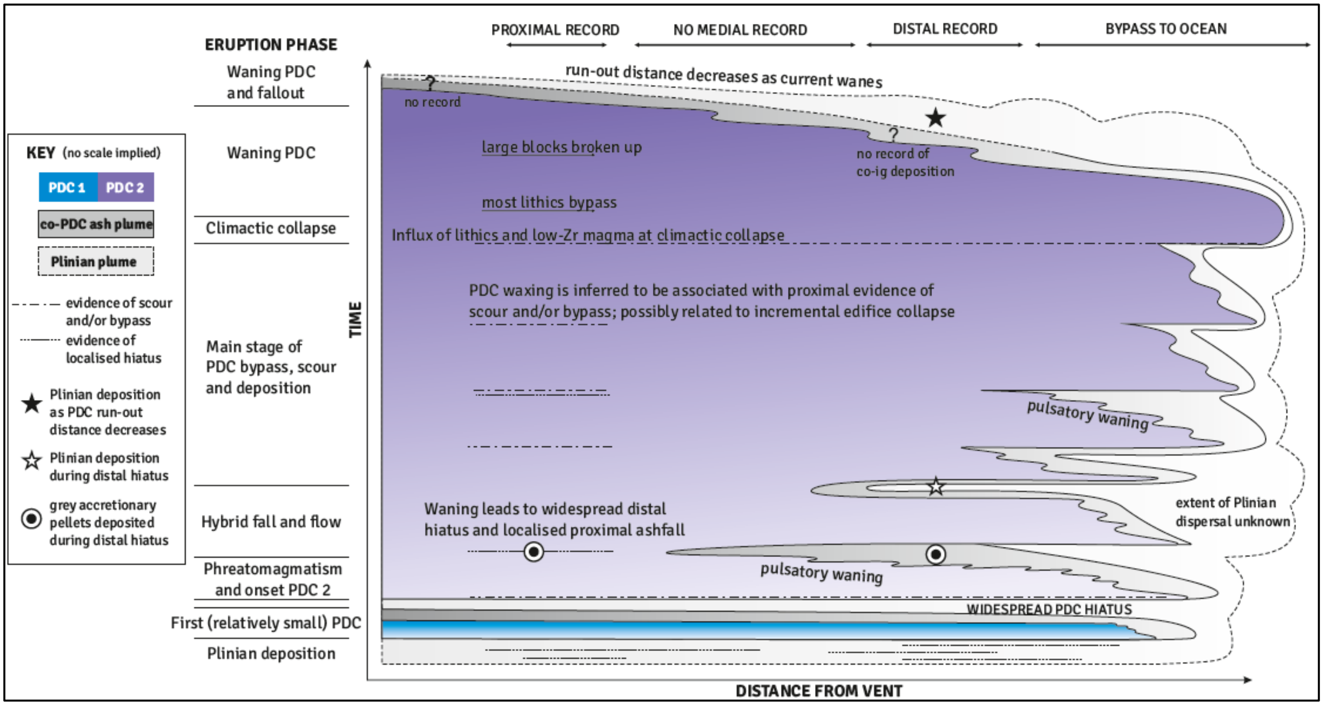

Figure 12: Schematic illustrating how PDC waxing and waning during the Poris eruption led to a conflicting record of flow units in proximal and distal zones

7. Discussion

7.1 Unsteadiness: what drives variable run out and hiatus?

Unsteadiness in PDCs, where a parameter such as velocity fluctuates through time *(e.g., Kneller & Branney, 1995)* can impact mobility and run-out distance but is poorly understood in dense, granular PDCs. Unsteadiness can manifest in pulsatory behaviour, the devastating impact of which was observed in real time during the 2018 eruption of Fuego volcano, Guatemala, where a series of pulses of valley-confined PDCs led to more than 400 fatalities (e.g., Charbonnier et al., 2023). Unsteadiness, current instabilities and pulsatory behaviour can be interpreted from the stratigraphic record (e.g., Pollock et al., 2019), and have been linked to fluctuating eruption conditions at the vent (e.g., Pittari et al., 2006; Báez et al., 2020). Unsteadiness generated by source conditions has been directly connected to mobility; increasing eruptive mass flux during Plinian events has been linked to increased run-out distance of pyroclastic density currents in both numerical modelling *(Bursik & Woods, 1996)* and field studies (Williams et al., 2014). However, it is important to note that source conditions are not the only driver of unsteadiness; experimental PDC modelling illustrates that poly-disperse dense granular currents are inherently unsteady under fluidised conditions, with pulses forming spontaneously even when a steady initial current is provided (Rowley et al., 2023 and references therein). Similar observations have been made in the modelling of other sustained gravity currents (such as turbidity currents; Kostaschuk et al., 2018).

In the case of the Poris eruption, influxes of lithics at ≥5 points in the proximal Poris succession (finely fragmented lithics during phase 3, at least three discrete lithic-rich pulses recorded in layers of tuff in phase 5, and the influx of lithic breccias of phase 6) are interpreted here to record episodes of waxing PDC activity. Each of these lithic episodes can be correlated with either resumption of PDC activity distally (increasing run out), stepping up of distal PDC intensity, or increased geographic extent of PDCs in the distal region. In this case, the influx of lithics indicates that instabilities at the vent are a likely driver for the waxing activity; waxing phase lithofacies during the second, sustained PDCs are each associated with influxes of lithics and/or banded pumices, indicating incremental destabilisation (and potentially, gradual expansion) of the edifice and inferring increased mass flux at source. These findings are similar to evidence from the younger 188 ka Abrigo ignimbrite of Tenerife, which has also been found to contain lithic block zones interpreted to result from pulses of vent-derived lithic debris attributed to the onset of caldera collapse (Pittari et al., 2006).

Whereas waxing activity is here linked to source conditions, there are indicators that waning activity may have involved episodes of spontaneous unsteadiness within the current. In this study, waning is recorded in proximal stratified units that correlate with reductions in run-out distally: stacked beds of coarse-tail grading of pumices in phase 3 proximal facies locally culminate in a discontinuous ash bed in the northern DH wall, marking local hiatus, and are correlated with a widespread hiatus in the distal region (grey ash pellet entrachron). In phase 4, stratification of the hybrid pumice block facies marks unsteady behaviour in the proximal zone and correlates to widespread distal hiatus marked by the deposition of the second Plinian unit (pale green pumice entrachron). The unsteady conditions recorded in the phase 3 repeated stacks of proximal inversely graded beds may have been caused by the pulsatory passage of spontaneously developed roll waves, shock-like disturbances that travel faster than the material in the flow (Balmforth & Mandre, 2004 and references therein). The pulsatory passage of roll waves is believed to be a contributing factor in the development of regularly stacked and thin pumiceous layers at ignimbrites elsewhere (e.g. Mount St. Helens July 22nd and August 7th 1980 deposits, and Santorini Minoan deposits, observed by PBK). Such waves, or pulses, have been seen in debris-flow flume experiments (Johnson et al., 2012), and have been observed to be directly involved in particle sorting processes and the development of reverse graded sets in fluidised granular flow analogue experiments (Rowley et al., 2023).

It is as yet unclear whether such features of spontaneous unsteadiness in PDCs could be intrinsically linked to waning regimes; they have been observed in both hopper release-style experiments that provide an insight into waxing-then-waning single-pulse type currents (Johnson et al., 2012) and also in a fluidised flume able to capture more sustained current behaviours; but not yet under controlled sustained waning conditions (Rowley et al., 2023). The potential scale of such features in nature is also unclear. To create the widespread decrease in run-out recorded in distal exposures at this time, it seems likely that larger-scale waning conditions at the vent may have been occurring, potentially in tandem with spontaneous current perturbations that created the distinctive repeating lithofacies.

7.2 Nonuniformity: the cause of spatial changes in lithofacies

While proximal to distal hiatus transitions reflect changes in runout distance due to unsteadiness through time, vent-radial lateral transitions in lithofacies are interpreted to record nonuniformity in space (Branney and Kokelaar, 2002). The discontinuous ash layers preserved in the very northern (phase 3) and southern (phase 5) fringes of the DH paleovalley are interpreted here to record nonuniform deposition with different drivers:

1. Reduced lateral extent: During episodes of waning activity and decreasing run out distance, it follows that lateral geographic extent may also decrease. This scenario seems likely to have caused restricted deposition of the proximal discontinuous ash layer in phase 3. The ash is associated with underlying graded facies indicating waning, and correlates with hiatus in the distal record. We infer that as the current waned, PDC activity no longer stretched across the entire DH wall and ash fallout occurred in the northern sector, contemporaneous with continued PDC activity (recorded in gradational contacts between phase 3 and 4) in the southern DH sector.
2. Thalweg migration: The second discontinuous proximal ash layer (phase 5) occurs at the southernmost DH outcrop, and is not associated with stratigraphic evidence of waning. Elsewhere, deposition of massive and lithic-rich layers of lapilli tuff records waxing PDC activity. The thalweg, the axis of flow and locus of deposition of a density-stratified current, may meander across a plain during periods of sustained aggradation from a PDC (e.g., Branney & Kokelaar, 1992; Watkins et al., 2002); it is possible that this

discontinuous ash layer may reflect temporary thalweg migration, rather than waning, which allowed ash to locally be deposited and preserved.

7.3 The influence of topography

Topographic changes have been shown to have a significant impact on deposition from pyroclastic density currents, for example by controlling locations of deposition (Branney & Kokelaar, 1997), influencing run out (Andrews & Manga, 2011), impacting sedimentation from the flow boundary zone (Doronzo et al., 2010) and channelising flow (Aravena & Roche, 2022). Topography may have a crucial influence on pulsatory and unsteady PDC behaviours - recent numerical modelling has shown that interactions between granular PDCs and topography can induce unsteadiness (E. Breard, pers. comm.). The impact of topography on PDCs, particular on dense granular PDCs, is not fully understood and requires further analogue and numerical modelling. However, the correlative work presented here shows that distinct topographic environments can lead to distinct deposition from the flow boundary zone at the same point in time in proximal and distal exposures; potentially contributing to contradictory records of eruption history in different locations. This builds upon previous work from other Quaternary ignimbrite sheets on Tenerife highlighting complex associations between paleotopography and unsteady PDC behaviours (Pittari et al., 2006).

During the Poris eruption, both caldera wall-scale and smaller-scale topographic obstacles across the Tenerife landscape caused local unsteadiness and lateral non-uniformity in PDC dynamics, during both waxing and waning phases of PDC activity. These impacts would have been dynamic; topographic variations and changes in substrate as a result of scour and infill were ongoing during the eruption both proximally and distally, at a range of scales.

For example, proximally, caldera topography acted as a barrier to flow in front of the Diego Hernandez site in the early stages of the Poris eruption. The Diego Hernandez paleovalley was part of pre-existing caldera topography that caused the first density current generated to be recorded in the DH wall merely as a thin veneer; the parts of the first current that surmounted it were fully dilute, turbulent and with traction at the base. Contemporaneously, parts of the current that reached the distal region were experiencing different conditions at the flow boundary zone, due to different topographic conditions. The presence of barrancos, ridges and topographic obstacles similar to Tenerife's present-day landscape led to the development of ignimbrite valley-fill and veneer lithofacies associations with complex internal architecture even in the earliest PDC deposits recorded in the distal zone (described in detail in Brown and Branney, 2004b and 2013).

7.4 The impact of proximity to the vent on ash deposition

Deposits proximal to the vent during Plinian eruptions are known to exhibit complex stratigraphy due to the varied processes acting in this zone (e.g., Houghton et al., 2004), but are often lost due to caldera collapse and subsequent near-vent erosion. The Poris succession is rare in having exposed proximal and distal counterparts, and - although apparently not as close to the Poris edifice as deposits in the Guajara sector of the wall were to their source (evidenced in welded units and conduit-infill material, see Soriano et al., 2006) - the proximal DH succession contains unique lithofacies, recording phreatomagmatism and hybrid processes not observed in the distal record (Smith and Kokelaar, 2013; Dowey and Williams, 2022). Particularly relevant to this study is evidence that proximity to the vent impacted the record of ash aggregates, key indicators of hiatus in the Poris record.

Distally, the PDC was the main source of ash during the Poris eruption. In the distal region, facies associations of topography-filling ignimbrite containing multi-rimmed AP2 accretionary lapilli, overlain by widespread layers of framework-supported AP1 ash pellets, are evidence of deposition by density-stratified PDCs followed by hiatus in PDC activity. The AP1 pellets formed in the co-ignimbrite plume fell into the density-stratified current and accreted rims to become AP2 pellets that were then deposited in ignimbrite. After the current passed by, the remaining AP1 pellets fell from the co-ignimbrite plume to form a clast-supported overlying layer (Brown et al., 2010).

The atmosphere in the near-plume zone would have been rich in ash and electrically charged, with scope for circulation towards and away from the hot plume axis and greater availability of water (originating for example from entrainment of moist tropospheric air or phreatomagmatism) (Brown et al., 2012 and references therein). In this proximal region ash aggregation can occur both within the vertical eruption plume and density-stratified currents (e.g., Bonadonna et al., 2002), potentially leading to different types of accretionary pellets becoming intermixed and deposited. The phase 2 proximal ash layer, which contains both AP1 and AP2 pellets of a similar size, is interpreted to reflect fallout of aggregates derived from both the eruption plume and the co-ignimbrite cloud of the first Poris PDC, at a time early in the eruption when PDC activity had ceased sufficiently for fragile unstructured ash pellets to be deposited and preserved.

7.4 The length of hiatus

It is difficult to estimate how long proximal and distal hiatuses in PDC activity lasted during the Poris event, and indeed how long the eruption itself lasted. Similar large-scale ignimbrites have been observed to derive from sustained currents lasting for minutes to hours (e.g., Pinatubo, 1991; Scott et al., 1996). It is known that ash aggregates can form quickly; AP1 aggregates were deposited within five minutes of the start of the 1990 eruption of Sakurajima volcano in Japan (Gilbert & Lane, 1994). In 1997, during two Vulcanian explosions at Soufriere Hills volcano, Montserrat produced an ashfall with a peak accumulation rate of 0.5-1.2 $x10^{-3}$ kg m^{-2} s^{-1} (Bonadonna et al., 2002). The ash fallout was accompanied by sedimentation of AP1 aggregates up to 4 mm in diameter, which began 15 minutes after the onset of the eruptions and lasted for 10-30 minutes. It seems conceivable that the phase 2 ash layer, correlated across both proximal and distal regions, could represent a fundamental hiatus in PDC activity of as little as tens of minutes, but possibly hours.

8. Implications

Evidence of unsteadiness and nonuniformity is common in both field studies and modelling of PDC activity (e.g., Doronzo et al., 2017; Andrews, 2019; G. Smith et al., 2020), with multiple factors at the vent, within the surrounding environment and landscape, and spontaneously within the current itself (Rowley et al., 2023) contributing to changes in behaviour at a range of spatial scales and timeframes. However, such changes in PDC behaviour are rarely illustrated in stratigraphic architecture at regional scale, from vent to distal reaches, due to lack of exposure.

This work reveals how correlation of distinct pyroclastic architecture deposited at different locations at the same point in time can impact our interpretations of eruption history. The correlation illustrates that (1) hiatuses in PDC activity recorded distally may not occur proximally, (2) hiatus in PDC activity can vary spatially (and potentially rapidly) due to large-scale changes in PDC dynamics in time and space, and (3) entrachron correlation across an ignimbrite sheet can reveal regional-scale PDC behaviours critical to our understanding of eruption history and hazard. The study highlights the uncertainties inherent in interpretations made without the presence of proximal stratigraphy, particularly when interpreting the number of pyroclastic density currents generated during a Plinian event. It provides a direct potential link between stratigraphic relationships observed in the field, and spontaneous behaviours observed in analogue experimental modelling that are difficult to observe during an eruption in real-time. Future developments in analogue modelling of fluidised granular flows (for example, replicating waning conditions) may provide insights that improve our understanding of the pulsatory PDC behaviours that generate unique stratigraphy.

Author contributions

This study is based upon correlation carried out during NJD's PhD research, which draws on the PhD research of RJB. NJD carried out proximal analysis, undertook correlative analysis, developed the concept and wrote the paper. RJD carried out distal analysis, contributed to discussions and co-wrote the paper. PBK carried out distal sampling, supervised both NJD and RJB and contributed to discussions.

Acknowledgements

NJD acknowledges Natural Environment Research Council studentship NE/G523855/1.

Data availability

All data presented in this work is available in full in the open access thesis of NJD located in a repository here: https://livrepository.liverpool.ac.uk/6253/

References

Ancochea, E., Fuster, M., Ibarrola, E., Cendrero, A., Coello, J., Hernan, F., Cantagrel, J. M., & Jamond, C. (1990). Volcanic evolution of the island of Tenerife (Canary Islands) in the light of new K-Ar data. In *Journal of Volcanology and Geothermal Research*.

Ancochea, E., Huertas, M. J., Cantagrel, J. M., Coello, J., Fúster, J. M., Arnaud, N., & Ibarrola, E. (1999). Evolution of the Cañadas edifice and its implications for the origin of the Cañadas Caldera (Tenerife, Canary Islands). *Journal of Volcanology and Geothermal Research*, *88*(3), 177–199. https://doi.org/https://doi.org/10.1016/S0377-0273(98)00106-1

Andrews, B. J. (2019). Recognizing unsteadiness in the transport systems of dilute pyroclastic density currents. *Bulletin of Volcanology*, *81*(2), 5. https://doi.org/10.1007/s00445-018-1266-5

Andrews, B. J., & Manga, M. (2011). Effects of topography on pyroclastic density current runout and formation of coignimbrites. *Geology*, *39*(12), 1099–1102. https://doi.org/10.1130/G32226.1

Aravena, A., & Roche, O. (2022). Influence of the topography of stratovolcanoes on the propagation and channelization of dense pyroclastic density currents analyzed through numerical simulations. *Bulletin of Volcanology*, *84*(7), 67. https://doi.org/10.1007/s00445-022-01576-2

Báez, W., de Silva, S., Chiodi, A., Bustos, E., Giordano, G., Arnosio, M., Suzaño, N., Viramonte, J. G., Norini, G., & Groppelli, G. (2020). Pulsating flow dynamics of sustained, forced pyroclastic density currents: insights from a facies analysis of the Campo de la Piedra Pómez ignimbrite, southern Puna, Argentina. *Bulletin of Volcanology*, *82*(7), 53. https://doi.org/10.1007/s00445-020-01385-5

Balmforth, N. J., & Mandre, S. (2004). Dynamics of roll waves. *Journal of Fluid Mechanics*, *514*, 1–33. https://doi.org/DOI: 10.1017/S0022112004009930

Bonadonna, C., Mayberry, G. C., Calder, E. S., Sparks, R. S. J., Choux, C., Jackson, P., Lejeune, A. M., Loughlin, S. C., Norton, G. E., Rose, W. I., Ryan, G., & Young, S. R. (2002). Tephra fallout in the eruption of Soufrière Hills Volcano, Montserrat. In *Geological Society, London, Memoirs* (Vol. 21, pp. 483–516). https://doi.org/10.1144/GSL.MEM.2002.021.01.22

Branney, M. J., & Kokelaar, P. (1992). *A reappraisal of ignimbrite emplacement: progressive aggradation and changes from particulate to non-particulate flow during emplacement of high-grade ignimbrite* (Vol. 54). Springer-Verlag.

Branney, M. J., & Kokelaar, P. (1997). Giant bed from a sustained catastrophic density current flowing over topography: Acatlán ignimbrite, Mexico. *Geology*, *25*(2), 115–118. https://doi.org/10.1130/0091-7613(1997)025<0115:GBFASC>2.3.CO;2

Branney, M. J., & Kokelaar, P. (2002). *Pyroclastic Density Currents and the Sedimentation of Ignimbrites*. Geological Society of London. https://doi.org/10.1144/GSL.MEM.2003.027

Brown, R. J. (2001). *Eruption history and depositional processes of the poris ignimbrite of Tenerife and the Glaramara Tuff of the English Lake District*. https://figshare.com/articles/Eruption_history_and_depositional_processes_of_the_poris_ignimbrite_of_Tenerife_and_the_Glaramara_Tuff_of_the_English_Lake_District/10091993

Brown, R. J., Barry, T. L., Branney, M. J., Pringle, M. S., & Bryan, S. E. (2003). The Quaternary pyroclastic succession of southeast Tenerife, Canary Islands: explosive eruptions, related caldera subsidence, and sector collapse. *Geological Magazine*, *140*(3), 265–288. https://doi.org/DOI: 10.1017/S0016756802007252

Brown, R. J., Bonadonna, C., & Durant, A. J. (2012). A review of volcanic ash aggregation. *Physics and Chemistry of the Earth*, *45–46*, 65–78. https://doi.org/10.1016/j.pce.2011.11.001

Brown, R. J., & Branney, M. J. (2004a). Bypassing and diachronous deposition from density currents: Evidence from a giant regressive bed form in the Poris ignimbrite, Tenerife, Canary Islands. *Geology*, *32*(5), 445–448. https://doi.org/10.1130/G20188.1

Brown, R. J., & Branney, M. J. (2004b). Event-stratigraphy of a caldera-forming ignimbrite eruption on Tenerife: The 273 ka Poris Formation. *Bulletin of Volcanology*, *66*(5), 392–416. https://doi.org/10.1007/s00445-003-0321-y

Brown, R. J., & Branney, M. J. (2013). Internal flow variations and diachronous sedimentation within extensive, sustained, density-stratified pyroclastic density currents flowing down gentle slopes, as revealed by the internal architectures of ignimbrites on Tenerife. *Bulletin of Volcanology*, *75*(7), 1–24. https://doi.org/10.1007/s00445-013-0727-0

Brown, R. J., Branney, M. J., Maher, C., & Dávila-Harris, P. (2010). Origin of accretionary lapilli within ground-hugging density currents: Evidence from pyroclastic couplets on Tenerife. *Bulletin of the Geological Society of America*, *122*(1–2), 305–320. https://doi.org/10.1130/B26449.1

Bryan, S. E., Cas, R. A. F., & Martí, J. (2000). The 0.57 Ma plinian eruption of the Granadilla Member, Tenerife (Canary Islands): an example of complexity in eruption dynamics and evolution. In *Journal of Volcanology and Geothermal Research* (Vol. 103). www.elsevier.nl/locate/jvolgeores

Bryan, S. E., Martí, J., & Cas, R. A. F. (1998). Stratigraphy of the Bandas del Sur Formation: an extracaldera record of Quaternary phonolitic explosive eruptions from the Las Cañadas edifice, Tenerife (Canary Islands). *Geological Magazine*, *135*(5), 605–636. https://doi.org/DOI: 10.1017/S0016756897001258

Bursik, M. I., & Woods, A. W. (1996). The dynamics and thermodynamics of large ash flows. *Bulletin of Volcanology*, *58*, 175–193.

Cas, R. A. F., Porritt, L., Pittari, A., & Hayman, P. (2008). A new approach to kimberlite facies terminology using a revised general approach to the nomenclature of all volcanic rocks and deposits: Descriptive to genetic. *Journal of Volcanology and Geothermal Research*, *174*(1), 226–240. https://doi.org/https://doi.org/10.1016/j.jvolgeores.2007.12.018

Cas, R. A. F., Wolff, J. A., Martí, J., Olin, P. H., Edgar, C. J., Pittari, A., & Simmons, J. M. (2022). Tenerife, a complex end member of basaltic oceanic island volcanoes, with explosive polygenetic phonolitic calderas, and phonolitic-basaltic stratovolcanoes. *Earth-Science Reviews*, *230*, 103990. https://doi.org/https://doi.org/10.1016/j.earscirev.2022.103990

Cas, R. A. F., & Wright, J. V. (1987). Volcanic Successions Modern and Ancient. *Volcanic Successions Modern and Ancient*. https://doi.org/10.1007/978-94-009-3167-1

Cavazos-Álvarez, J. A., & Carrasco-Núñez, G. (2020). Anatomy of the Xáltipan ignimbrite at Los Humeros Volcanic Complex; the largest eruption of the Trans-Mexican Volcanic Belt. *Journal of Volcanology and Geothermal Research*, *392*, 106755. https://doi.org/https://doi.org/10.1016/j.jvolgeores.2019.106755

Charbonnier, S. J., Garin, F., Rodríguez, L. A., Ayala, K., Cancel, S., Escobar-Wolf, R., Chigna, G., Chun-Quinillo, C., González, D., Chigna, W., Chun-Quinillo, K., Mérida, R., Juarez, F., & Calder, E. S. (2023). Unravelling the dynamics and hazards of the June 3rd, 2018, pyroclastic density currents at Fuego volcano (Guatemala). *Journal of Volcanology and Geothermal Research*, *436*, 107791. https://doi.org/https://doi.org/10.1016/j.jvolgeores.2023.107791

Dávila Harris, P., Branney, M. J., & Storey, M. (2011). Large eruption-triggered ocean-island landslide at Tenerife: Onshore record and long-term effects on hazardous pyroclastic dispersal. *Geology*, *39*(10), 951–954. https://doi.org/10.1130/G31994.1

Dávila Harris, P., Branney, M. J., Storey, M., Taylor, R. N., & Sliwinski, J. T. (2023). The upper Pleistocene (1.8–0.7 Ma) explosive eruptive history of Las Cañadas, ocean-island volcano, Tenerife. *Journal of Volcanology and Geothermal Research*, *436*, 107777. https://doi.org/https://doi.org/10.1016/j.jvolgeores.2023.107777

Dávila Harris, P., Ellis, B. S., Branney, M. J., & Carrasco-Núñez, G. (2013). Lithostratigraphic analysis and geochemistry of a vitric spatter-bearing ignimbrite: the Quaternary Adeje Formation, Cañadas volcano, Tenerife. *Bulletin of Volcanology*, *75*(6), 722. https://doi.org/10.1007/s00445-013-0722-5

Doronzo, D. M., Dellino, P., Sulpizio, R., & Lucchi, F. (2017). Merging field mapping and numerical simulation to interpret the lithofacies variations from unsteady pyroclastic density currents on uneven terrain: The case of La Fossa di Vulcano (Aeolian Islands, Italy). *Journal of Volcanology and Geothermal Research*, *330*, 36–42. https://doi.org/https://doi.org/10.1016/j.jvolgeores.2016.11.016

Doronzo, D. M., Valentine, G. A., Dellino, P., & de Tullio, M. D. (2010). Numerical analysis of the effect of topography on deposition from dilute pyroclastic density currents. *Earth and Planetary Science Letters*, *300*(1), 164–173. https://doi.org/https://doi.org/10.1016/j.epsl.2010.10.003

Dowey, N., & Williams, R. (2022). Simultaneous fall and flow during pyroclastic eruptions: A novel proximal hybrid facies. *Geology*, *50*(10), 1187–1191. https://doi.org/10.1130/G50169.1

Druitt, T. H. (1998). Pyroclastic density currents. *Geological Society, London, Special Publications*, *145*(1), 145–182. https://doi.org/10.1144/GSL.SP.1996.145.01.08

Dufek, J., Esposti Ongaro, T., & Roche, O. (2015). Pyroclastic density currents: processes and models. Chapter 35. *Part IV Explosive Volcanism, The Encyclopedia of Volcanoes*.

Edgar, C. J., Wolff, J. A., Nichols, H. J., Cas, R. A. F., & Martí, J. (2002). A complex Quaternary ignimbrite-forming phonolitic eruption: the Poris Member of the Diego Hernández Formation (Tenerife, Canary Islands). *Journal of Volcanology and Geothermal Research*, *118*(1), 99–130. https://doi.org/https://doi.org/10.1016/S0377-0273(02)00252-4

Edgar, C. J., Wolff, J. A., Olin, P. H., Nichols, H. J., Pittari, A., Cas, R. A. F., Reiners, P. W., Spell, T. L., & Martí, J. (2007). The late Quaternary Diego Hernandez Formation, Tenerife: Volcanology of a complex cycle of voluminous explosive phonolitic eruptions. *Journal of Volcanology and Geothermal Research*, *160*(1–2), 59–85. https://doi.org/10.1016/j.jvolgeores.2006.06.001

Fierstein, J., Houghton, B. F., Wilson, C. J. N., & Hildreth, W. (1997). Complexities of plinian fall deposition at vent: An example from the 1912 Novarupta eruption (Alaska). *Journal of Volcanology and Geothermal Research*, *76*(3–4), 215–227. https://doi.org/10.1016/S0377-0273(96)00081-9

Fierstein, J., & Wilson, C. J. N. (2005). Assembling an ignimbrite: Compositionally defined eruptive packages in the 1912 Valley of Ten Thousand Smokes ignimbrite, Alaska. *GSA Bulletin*, *117*(7–8), 1094–1107. https://doi.org/10.1130/B25621.1

Fisher, R. V. (1966). Mechanism of deposition from pyroclastic flows. *American Journal of Science*, *264*(5), 350–363.

Fisher, R. V, Orsi, G., Ort, M., & Heiken, G. (1993). Mobility of a large-volume pyroclastic flow — emplacement of the Campanian ignimbrite, Italy. *Journal of Volcanology and Geothermal Research*, *56*(3), 205–220. https://doi.org/https://doi.org/10.1016/0377-0273(93)90017-L

Fisher, R. V., & Schmincke, H.-U. (1984). Pyroclastic Flow Deposits. *Pyroclastic Rocks*, 186–230. https://doi.org/10.1007/978-3-642-74864-6_8

Gase, A. C., Brand, B. D., & Bradford, J. H. (2017). Evidence of erosional self-channelization of pyroclastic density currents revealed by ground-penetrating radar imaging at Mount St. Helens, Washington (USA). *Geophysical Research Letters*, *44*(5), 2220–2228. https://doi.org/https://doi.org/10.1002/2016GL072178

Gilbert, J. S., & Lane, S. J. (1994). The origin of accretionary lapilli. *Bulletin of Volcanology*, *56*(5), 398–411. https://doi.org/10.1007/BF00326465

Gooday, R. J., Brown, D. J., Goodenough, K. M., & Kerr, A. C. (2018). A proximal record of caldera-forming eruptions: the stratigraphy, eruptive history and collapse of the Palaeogene Arran caldera, western Scotland. *Bulletin of Volcanology*, *80*(9), 70. https://doi.org/10.1007/s00445-018-1243-z

Houghton, B. F., Wilson, C. J. N., Fierstein, J., & Hildreth, W. (2004). Complex proximal deposition during the Plinian eruptions of 1912 at Novarupta, Alaska. *Bulletin of Volcanology*, *66*(2), 95–133. https://doi.org/10.1007/s00445-003-0297-7

Johnson, C. G., Kokelaar, B. P., Iverson, R. M., Logan, M., LaHusen, R. G., & Gray, J. M. N. T. (2012). Grain-size segregation and levee formation in geophysical mass flows. *Journal of Geophysical Research: Earth Surface*, *117*(F1). https://doi.org/https://doi.org/10.1029/2011JF002185

Kneller, B. C., & Branney, M. J. (1995). Sustained high-density turbidity currents and the deposition of thick massive sands. *Sedimentology*, *42*(4), 607–616. https://doi.org/10.1111/J.1365-3091.1995.TB00395.X

Kostaschuk, R., Nasr-Azadani, M. M., Meiburg, E., Wei, T., Chen, Z., Negretti, M. E., Best, J., Peakall, J., & Parsons, D. R. (2018). On the Causes of Pulsing in Continuous Turbidity Currents. *Journal of Geophysical Research: Earth Surface*, *123*(11), 2827–2843. https://doi.org/https://doi.org/10.1029/2018JF004719

Lube, G., Breard, E. C. P., Esposti-Ongaro, T., Dufek, J., & Brand, B. (2020). Multiphase flow behaviour and hazard prediction of pyroclastic density currents. *Nature Reviews Earth & Environment*, *1*(7), 348–365. https://doi.org/10.1038/s43017-020-0064-8

Lube, G., Cronin, S. J., Platz, T., Freundt, A., Procter, J. N., Henderson, C., & Sheridan, M. F. (2007). Flow and deposition of pyroclastic granular flows: A type example from the 1975 Ngauruhoe eruption, New Zealand. *Journal of Volcanology and Geothermal Research*, *161*(3), 165–186. https://doi.org/https://doi.org/10.1016/j.jvolgeores.2006.12.003

Martí, J. (2019). Las Cañadas caldera, Tenerife, Canary Islands: A review, or the end of a long volcanological controversy. *Earth-Science Reviews*, *196*, 102889. https://doi.org/https://doi.org/10.1016/j.earscirev.2019.102889

Martí, J., Mitjavila, J., & Araña, V. (1994). Stratigraphy, structure and geochronology of the Las Cañadas caldera (Tenerife, Canary Islands). *Geological Magazine*, *131*(6), 715–727. https://doi.org/DOI: 10.1017/S0016756800012838

Marti, J., Mitjavila, J., & Villa, I. (1990). Stratigraphy and K-Ar ages of the Diego Hernandez wall and their significance on the Las Cafiadas Caldera formation (Tenerife, Canary Islands). *Terra Nova*, *2*(2), 148–153.

Mues-Schumacher, U., & Schumacher, R. (1996). Problems of Stratigraphic Correlation and New K-Ar Data for Ignimbrites from Cappadocia, Central Turkey. *International Geology Review*, *38*(8), 737–746. https://doi.org/10.1080/00206819709465357

Myers, M. L., Wallace, P. J., Wilson, C. J. N., Morter, B. K., & Swallow, E. J. (2016). Prolonged ascent and episodic venting of discrete magma batches at the onset of the Huckleberry Ridge supereruption, Yellowstone. *Earth and Planetary Science Letters*, *451*, 285–297. https://doi.org/10.1016/J.EPSL.2016.07.023

Pittari, A., Cas, R. A. F., Edgar, C. J., Nichols, H. J., Wolff, J. A., & Martí, J. (2006). The influence of palaeotopography on facies architecture and pyroclastic flow processes of a lithic-rich ignimbrite in a high gradient setting: The Abrigo Ignimbrite, Tenerife, Canary Islands. *Journal of Volcanology and Geothermal Research*, *152*(3–4), 273–315. https://doi.org/10.1016/j.jvolgeores.2005.10.007

Pollock, N. M., Brand, B. D., Rowley, P. J., Sarocchi, D., & Sulpizio, R. (2019). Inferring pyroclastic density current flow conditions using syn-depositional sedimentary structures. *Bulletin of Volcanology*, *81*(8), 1–16. https://doi.org/10.1007/S00445-019-1303-Z/FIGURES/7

Ross, C. S., & Smith, R. L. (1961). Ash-flow tuffs: Their origin, geologic relations, and identification. In *Professional Paper*. https://doi.org/10.3133/pp366

Rowley, P., Williams, R., Johnson, M., Johnston, T., Dowey, N., Parson, D. P., Provost, A., Roche, O., Smith, G. M., & Walding, N. (2023). Spontaneous Unsteadiness and Sorting in Pyroclastic Density Currents and their Deposits. *EarthArxiv Preprint*.

Scott, W. E., Hoblitt, R. P., Torres, R. C., Self, S., Martinez, M. L., & Nillos, T. J. (1996). Pyroclastic flows of the June 15 1991, climactic eruption of Mount Pinatubo. In C. G. Newhall & S. Punongbayan (Eds.), *Fire and mud: eruptions of Pinatubo, Philippines* (pp. 545–570). University of Washington Press.

Sigurdsson, H., & Carey, S. (1989). Plinian and co-ignimbrite tephra fall from the 1815 Tambora eruption. *Bulletin of Volcanology*, *51*(4), 243–270. https://doi.org/10.1007/BF01073515

Silva Parejas, C., Druitt, T. H., Robin, C., Moreno, H., & Naranjo, J.-A. (2010). The Holocene Pucón eruption of Volcán Villarrica, Chile: deposit architecture and eruption chronology. *Bulletin of Volcanology*, *72*(6), 677–692. https://doi.org/10.1007/s00445-010-0348-9

Smith, G., Rowley, P., Williams, R., Giordano, G., Trolese, M., Silleni, A., Parsons, D. R., & Capon, S. (2020). A bedform phase diagram for dense granular currents. *Nature Communications*, *11*(1), 1–11. https://doi.org/10.1038/s41467-020-16657-z

Smith, N. (2012). *Near-vent processes of the 273 ka Poris eruption (Tenerife)* [Unpublished Thesis, University of Liverpool]. https://livrepository.liverpool.ac.uk/6253/

Smith, N., & Kokelaar, B. P. (2013). Proximal record of the 273 ka Poris caldera-forming eruption, Las Cañadas, Tenerife. *Bulletin of Volcanology*, *75*(11), 768–789. https://doi.org/10.1007/s00445-013-0768-4

Soriano, C., Galindo, I., Martí, J., & Wolff, J. (2006). Conduit-vent structures and related proximal deposits in the Las Cañadas caldera, Tenerife, Canary Islands. *Bulletin of Volcanology*, *69*(2), 217–231. https://doi.org/10.1007/s00445-006-0069-2

Sparks, R. S. J. (1976). Grain size variations in ignimbrites and implications for the transport of pyroclastic flows. *Sedimentology*, *23*(2), 147–188. https://doi.org/https://doi.org/10.1111/j.1365-3091.1976.tb00045.x

Sparks, R. S. J., Self, S., & Walker, G. P. L. (1973). Products of Ignimbrite Eruptions. *Geology*, *1*(3), 115–118. https://doi.org/10.1130/0091-7613(1973)1<115:POIE>2.0.CO;2

Sparks, R. S. J., & Walker, G. P. L. (1977). The significance of vitric-enriched air-fall ashes associated with crystal-enriched ignimbrites. *Journal of Volcanology and Geothermal Research*, *2*(4), 329–341. https://doi.org/https://doi.org/10.1016/0377-0273(77)90019-1

Sulpizio, R., Dellino, P., Doronzo, D. M., & Sarocchi, D. (2014). Pyroclastic density currents: state of the art and perspectives. *Journal of Volcanology and Geothermal Research*, *283*, 36–65. https://doi.org/10.1016/J.JVOLGEORES.2014.06.014

Watkins, S. D., Giordano, G., Cas, R. A. F., & De Rita, D. (2002). Emplacement processes of the mafic Villa Senni Eruption Unit (VSEU) ignimbrite succession, Colli Albani volcano, Italy. *Journal of Volcanology and Geothermal Research*, *118*(1), 173–203. https://doi.org/https://doi.org/10.1016/S0377-0273(02)00256-1

Williams, R., Branney, M. J., & Barry, T. L. (2014). Temporal and spatial evolution of a waxing then waning catastrophic density current revealed by chemical mapping. *Geology*, *42*(2), 107–110. https://doi.org/10.1130/G34830.1

Wilson, C. J. N. (1985). The Taupo eruption, New Zealand. II. The Taupo Ignimbrite. *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences*, *314*(1529), 229–310. https://doi.org/10.1098/RSTA.1985.0020

Wilson, C. J. N., & Hildreth, W. (1997). The Bishop Tuff: New Insights from Eruptive Stratigraphy. *The Journal of Geology*, *105*(4), 407–440. https://doi.org/10.1086/515937

Wilson, C. J. N., & Hildreth, W. (1998). Hybrid fall deposits in the Bishop Tuff, California: A novel pyroclastic depositional mechanism. *Geology*, *26*(1), 7–10.