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**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 well-exposed ignimbrites on
Tenerife**

Richard J. Brown¹ and Michael J. Branney²

¹Department of Earth Sciences, Durham University, Durham, DH1 3LE, UK

²Geology Department, University of Leicester, University Road, Leicester, LE1 7RH, UK

*Corresponding author: richard.brown3@durham.ac.uk

ABSTRACT

During a protracted explosive eruption, at least four laterally extensive and sustained pyroclastic density currents radiated across the flanks of Las Cañadas volcano, Tenerife. Each pyroclastic current developed marked local and regional spatial variations in response to the incised, gently concave substrate topography. The locations of these variations shifted in space as rapid sedimentation from the current progressively buried and modified the topography. This complex, shifting response of the density currents to minor topographic variations has been reconstructed in high-resolution over a wide area (>500 km²) using the internal architecture of cryptic time-surfaces ('entrachrons') marked by compositional zoning in the deposit, including variations in clast types. Valley-side field relations reveal that the currents were density-stratified. At a single instant in time, the lower levels of each current comprised a granular-fluid at some locations but were fully dilute and turbulent at others. However, the locations of these variations shifted geographically as the topography changed during the eruption. The variations within the current are recorded by numerous superbly-exposed gradational transitions from various stratified to massive lithofacies, both laterally and in the downcurrent

direction. Individual currents were regionally widespread and travelled >15 km, but deposited only in longitudinally-restricted, localised zones that spanned several small valleys and interfluvies. The currents bypassed slopes upcurrent and downcurrent of the restricted depositional zones, without depositing. The locations of deposition then gradually shifted with time, such that the extensive deposit sheet was gradually assembled beneath the sustained current in a diachronous fashion. Onlap relationships of internal entrachrons reveal that the base of the ignimbrite sheet and even the bases of individual flow-units are markedly diachronous. Deposition of a flow-unit commenced and ceased at different times in different places. This study suggests that in hazard assessments: (A) models of density currents that incorporate only pre-existing topography (e.g. from DEMs) may give misleading results in the case of sustained currents, because sedimentation from these significantly modifies the topography during emplacement, altering flow paths; (B), frequencies and scales of previous pyroclastic currents determined from pyroclastic successions are likely to be significantly underestimated because currents commonly bypass without leaving a deposit record; and (C) even where preservation appears to be complete, an ignimbrite at a single exposure commonly will not record the current's entire flow history at that site.

42

Keywords: ignimbrite, pyroclastic density current, topography, volcanic hazard, Plinian eruption

44

45 Introduction

How density currents interact with substrate topography is of interest to workers on marine turbidite basins, volcanoes, and flood-prone regions (e.g., Fisher 1990, 1995; Valentine et al. 1992; Alexander and Morris 1994; De Rita et al. 1998; Kneller and McCaffrey 1999; Bursik and Woods 2000; Legros and Kelfoun 2000; Kubo 2004; Sulpizio et al. 2008; Doronzo et al. 2010; Gurioli et al. 2010; Lube et al. 2011; Andrews and Manga 2011; Doronzo and Dellino 2012). It is of particular importance to those who work on volcanic hazards at densely populated volcanoes (e.g., Bourdier and Abdurachman 2001; Lirer et al. 2001; Rossano et al. 2004; see also Doronzo and Dellino 2012; Gertisser et al., 2012).

53 Deposition from particulate gravity currents is fundamentally influenced by substrate topography, and
54 most volcanoes are characterised by substantial relief (e.g., cones, craters and calderas) and many are
55 incised by gullies and valleys. Deposition from density currents typically relates to decelerations
56 resulting from flow divergence (radial flow) or flow down concave slopes (depletive flow; Kneller and
57 Branney 1995; Branney and Kokelaar 2002), including across breaks-in-slope at the base of a volcanic
58 cone, or as a result of encounters with an obstacle in the flow path, as demonstrated in the field, in the
59 laboratory and through modelling (e.g., Valentine, 1987; Macias et al. 1998; Woods et al. 1998;
60 Sulpizio et al. 2007, 2008, 2010; Gurioli et al., 2010; see reviews by Druitt 1998; Branney and
61 Kokelaar 2002; Sulpizio and Dellino 2008). In the past decade, understanding the nature and behaviour
62 of pyroclastic density currents (PDCs) has gained from focus on observed small-volume dome-collapse
63 and Vulcanian eruptions (e.g., Calder et al. 1999; Loughlin et al. 2002; Druitt et al. 2002). Witnessed
64 currents of this type were small-volume, short-lived and depletive, and affected relatively small areas,
65 mostly along valley floors. In contrast, large-volume, radiating PDCs, associated with some large
66 Plinian eruptions, pose a far greater hazard: they are regionally extensive, and they inundate vast areas
67 including over topographic highs within just seconds to hours.

68 This paper focuses on large-volume radiating density currents, to explore (A) the role of
69 topography, of a range of scales, in influencing deposition from a density current, and (B) how
70 topography changes as a result of deposition by the current. Our analysis draws on an extensive data set
71 of a complex, 3-dimensional internal architecture within a low-aspect ratio ignimbrite sheet, the 273 ka
72 Poris ignimbrite on Tenerife (Edgar et al 2002; Brown et al 2003; Brown and Branney 2004a). This
73 deposit is widespread and was deposited by at least four sustained pyroclastic density currents across
74 irregular topography (Brown and Branney 2004a). The Poris ignimbrite is instructive because it is
75 laterally widespread (500 km³), compositionally zoned and particularly well-exposed and dissected:
76 these features are not commonly presented together. Detailed logging of 85 vertical sections has
77 enabled us to trace time-surfaces ('entrachrons' of Branney and Kokelaar 2002) through the interior of
78 the ignimbrite sheet from valley-to-valley across interfluves and ridges, and also in the downcurrent

79 direction. This has allowed us to reconstruct temporal and spatial variations within the sustained
80 currents on both local and regional scales; how these variations evolved rapidly during the eruption;
81 and how deposition from each density current was highly localised and accompanied by widespread
82 bypassing, resulting in a patchy, incomplete record of the flow history at any individual location. We
83 regard such density current behaviour to typify the behaviour of larger, prolonged density currents on
84 gentle slopes, this increases the potential to underestimate the frequency, duration and dispersal of
85 PDCs in field studies. The study illustrates the importance of meticulous fieldwork in determining the
86 hazards posed by PDC-forming eruptions at large volcanoes. This is of particular importance for
87 volcanoes near the sea because much of the depositional mass transported by PDCs may end-up
88 concealed offshore.

89

90 **The sedimentation of ignimbrite**

91 The depositional mechanisms of catastrophic currents that produce large ignimbrites are thought to be
92 gradational between fluid-modified granular flows and particle-bearing fluids (Branney and Kokelaar
93 2002). Such gradational currents are poorly understood. Direct observation of their deposition is
94 impossible, not least because they are capricious, opaque and hazardous. Over the past three decades
95 studies on the architecture of large ignimbrite sheets (e.g., Taupo ignimbrite, New Zealand, Wilson and
96 Walker 1985; Valley of Ten Thousand Smokes ignimbrite, Alaska, Fierstein and Hildreth 1992;
97 Fierstein and Wilson 2005; 1991 eruption of Pinatubo, Philippines, Scott et al. 1996; Branney and
98 Kokelaar 2002; Zaragoza ignimbrite, Mexico, Carrasco-Núñez and Branney 2005) have provided
99 insights into the depositional mechanisms of PDCs. Our understanding of the transport and deposition
100 of ignimbrite derives largely from inferences from such deposits, from laboratory experiments (e.g.
101 Choux and Druitt, 2002; Roche et al. 2005, 2011; Girolami et al. 2010; Roche 2012) and the numerical
102 modelling of selected physical parameters (e.g. Valentine 1987; Dade and Huppert 1996; Woods et al
103 1998; Druitt 1998; Denlinger and Iverson 2001; Burgisser and Bergantz 2002; Dufek et al., 2009;
104 Doronzo et al. 2010; Andrews and Manga 2012). However, models and experiments are not yet

105 sufficiently sophisticated to account for the range of common ignimbrite lithofacies, nor their complex
106 architectures.

107 Large-volume ignimbrites derive from protracted currents that may last for minutes to hours
108 (e.g., 1991 eruption of Pinatubo, Philippines, Scott et al. 1996). The deposits of sustained particulate
109 density currents can be complex, and exhibit rapid vertical and lateral lithofacies transitions (e.g. Scott
110 et al. 1996; Bryan et al. 1998b; Allen and Cas 1998; Brown and Branney 2004a, 2004b; Pittari et al.
111 2006). This complexity has led workers to consider that sustained currents are inhomogeneous in both
112 space and time, i.e., their velocity, concentration, capacity and rheology can change spatially and
113 temporally during transport and deposition (e.g., Branney and Kokelaar 1992, 2002; Kneller and
114 McCaffrey 1991; Best et al. 2005; Andrews and Manga 2012). In such currents a range of different
115 clast-support mechanisms operate in tandem during transport and deposition (Branney and Kokelaar
116 2002), so that adjacent clasts within the resulting ignimbrite may have had different transport histories.
117 Flow directions of sustained density currents also vary with time at individual locations (Kneller et al.
118 1999; Morris and Alexander 2003; Branney et al. 2004; Andrews and Branney 2012).

119 The depositional mechanisms of sustained PDCs are fundamentally influenced by lower flow-
120 boundary conditions, which as the result of density stratification in the current will differ significantly
121 from conditions higher in the current (Fisher 1966; Valentine 1987; Branney and Kokelaar 1992, 1997,
122 2002; Sohn 1997; Sulpizio et al. 2007; Sulpizio and Dellino, 2008). The flow-boundary zone includes
123 the basal part of the current and the uppermost part of the deposit, and it rises as the deposit aggrades.
124 Over the past decade researchers have recognised a continuum of flow-boundary zone conditions that
125 give rise to a range of PDC deposit types as a function of current velocity, shear rate, and particle
126 concentration in the lower parts of the current, and sedimentation rate (e.g., Branney and Kokelaar
127 2002; Burgisser and Bergantz 2002; Sulpizio et al. 2007).

128 Branney and Kokelaar (2002) proposed that four intergradational end-member types of flow-
129 boundary (direct-fallout-dominated, traction-dominated, granular flow-dominated and fluid-escape-
130 dominated) account for the range of common lithofacies in ignimbrites. Each end-member type of

131 flow-boundary zone is characterised by distinctive velocity and concentration gradients, yet they are
132 considered transitional into one another with changing rates of concentration, deposition and shear. The
133 vertical succession of lithofacies within the deposit of a sustained current records the changing
134 conditions and depositional processes with time (unsteadiness), while the lateral lithofacies variations
135 along an entrachron record spatial variations during a single moment in time (non-uniformity, see
136 Kneller and McCaffrey 1999; Choux and Druitt 2002; Branney and Kokelaar 2002).

137

138 **Eruptive history and morphology of Las Cañadas volcano**

139 Tenerife is composed of a large ignimbrite shield volcano, Las Cañadas volcano, constructed on
140 coalesced and eroded basaltic shield volcanoes (Ancochea et al. 1990; 1999; Martí et al. 1994; Fig. 1).
141 Numerous Plinian eruptions have occurred in the past 2 Ma (Ancochea et al. 1990; Huertas et al. 2002;
142 Brown et al. 2003; Dávila Harris, 2009; Dávila Harris et al. 2011). These deposited ignimbrites, and
143 pumice and ash fall deposits across the island. The pyroclastic deposits are interleaved with numerous
144 basaltic lavas from scattered monogenetic flank volcanoes, and from three volcanic rift-zones (Bryan et
145 al. 1998a, b; Bryan et al. 2000; Pittari et al., 2006; Dávila Harris 2009; Dávila Harris et al. 2012). The
146 southern flank of Las Cañadas volcano rises to 2.5 km above sea-level and drops abruptly back down to
147 0.5 km into the central caldera (Figs 1 and 2). For the purposes of this paper we consider that the
148 southern flanks include a 180° sector that stretches from the north side of the Güimar valley to Guia de
149 Isora in the west (Fig. 2). This southern flank is broadly concave, from steeper upper flanks (9–15°;
150 Fig. 2) to lower gradient (<6°) coastal flanks (<200 m altitude; the Bandas del Sur) that reach as much
151 as 5 km inland from the coast. The flank varies from 15–20 km wide. In detail, the lower gradient
152 apron is not continuous and forms a coastal crescent that stretches from Los Cristianos in the west to
153 just north of Poris de Abona. The eastern end of the southern flank of Tenerife is abruptly terminated
154 by the partly filled Güimar collapse scarp, which is the result of one of several large sector-collapse
155 landslides that have occurred on Tenerife over the past 2 Ma (Watts and Masson 2001; Dávila Harris et
156 al. 2011).

The Bandas del Sur has a semi-arid climate prone to periodic flash floods, which have incised the slopes to produce a network of downhill-converging radial valleys. Palaeotopography indicates that the region has had a similar topography for the past 2 Ma (Pittari et al. 2006). Valleys and palaeo-valleys are 10–50 m deep, 10's to 100's of metres wide, and are separated by hundreds of metres-wide, flat-topped interfluves and narrower ridges (Fig. 1).

Terminology

We use pyroclastic density current (PDC) for any type of gaseous gravity current carrying pyroclastic material (i.e. including both ‘fully-dilute’ and ‘granular fluid-based’ types; Branney and Kokelaar 2002), and we use ignimbrite for the pumiceous deposit of a PDC (including ash-rich deposits). The term ignimbrite sheet is used to describe a succession of ignimbrites and subordinate fall deposits deposited during one eruption. We use the term valley-fill to describe those parts of the ignimbrite sheet deposited within valleys and the term veneer in a non-genetic sense, to describe topography-draping, thinner ignimbrite deposited on topographic highs (similar to ‘overbank facies’ of Schumacher and Schmincke 1990): no inference of deposition from the ‘tail’ of a PDC is implied (cf. IVDs of Walker et al. 1981). The term flow-unit is used to define an ignimbrite bounded by horizons (such as fall deposits, reworking, scours) that indicate pauses in current activity at that site. Lithofacies are summarised in Brown and Branney (2004a). We use the term entrachron to describe a cryptic surface within an ignimbrite that links together clasts that entered the current at the same time (e.g., a new type of juvenile material) and depochron to describe a cryptic surface that links together clasts that were deposited at the same time. We use the lithostratigraphic term ‘member’ for a lithologically-distinctive division that has regional distribution (see Brown and Branney 2004a): members do not necessarily correspond to individual flow-units.

181 **Ignimbrite architecture of the Poris Formation**

182 The 273 ka Poris Formation (Bryan et al. 1998a; Edgar et al. 2002; Brown et al. 2003; Brown and
183 Branney 2004a) lies within the Quaternary Bandas del Sur Group of Tenerife (Fig. 2). It is a compound
184 phonolite to tephri-phonolite ignimbrite sheet, composed of several ignimbrite flow-units with
185 associated co-ignimbrite ash fall layers and pumice fall deposits emplaced during a Plinian eruption
186 (Fig. 3). It outcrops in the Diego Hernandez sector of Las Cañadas' caldera wall (Edgar et al. 2002;
187 Smith 2012) and along the southeast coast (Fig. 4; Bryan et al. 1998a; Edgar et al. 2002; Brown et al.
188 2004a). Proximal sections of the ignimbrite sheet are interpreted in Smith (2012). The present study
189 focuses on the coastal ignimbrite sheet, which is widely 2–35 m thick and emplaced across a gently
190 concave volcano flank cut by small dendritic valleys (10–40 m deep), separated by broad interfluvies,
191 which it variously draped and buried along a 50 km-long coastal strip (from Montaña Guaza near Los
192 Christianos in the south, to El Baul in the northeast, Fig. 1).

193 The Poris Formation has been subdivided into eleven lithostratigraphic members and includes
194 four ignimbrite flow-units (Fig. 3; Brown and Branney 2004a). Each of the four flow-units is separated
195 by clear evidence for pauses in density current activity (e.g., pumice or ash fall layers, or eroded
196 remnants of these). Flow-units 1–3 are composed mostly of massive lapilli-tuff within palaeovalleys
197 and extensive ash layers across palaeo-ridges (Fig. 3). Flow-unit 4 is zoned, allowing it to be divided
198 into four distinct lithostratigraphic members, and can be traced across the entire width of the Bandas
199 del Sur (Fig. 4). Its compositional zoning has the form of compositional variations with height in the
200 deposit, in the form of cryptic entrachrons that mark the entrances and exits of various distinctive
201 components, including accretionary lapilli, abundant lithic clasts, and juvenile banded tephri-phonolite
202 pumice clasts. However, there is no evidence within the flow-unit for the cessation of flow (i.e., no ash
203 fall layers or reworking; see Brown and Branney 2004a). Moulds of allochthonous tree trunks are
204 common in Flow-unit 4.

205

206 **Distribution of ignimbrite flow-units of the Poris Formation**

207 The distribution of each flow-unit varies considerably (Fig. 4). Flow-units 1 and 2 are restricted to a
208 10–20 km-wide zone in central parts of the Bandas del Sur (mostly between Tajao and Poris de Abona,
209 Figs. 1 and 4). As they were the first ignimbrites to be emplaced they were thickest along valley axes,
210 but the thickest valley fills have been eroded and the ignimbrites are preserved mostly as remnants
211 along palaeo-valley sides and as centimetre-thick veneers over palaeo-ridges. The maximum preserved
212 thicknesses are 2.6 m (Flow-unit 1 at Montaña Magua) and 2.2 m (Flow-unit 2). Flow-unit 3 outcrops
213 between La Caleta and Montaña Magua (Fig. 1) and is preserved up to 93 cm thick in palaeo-valleys
214 (between Tajao and La Caleta, Fig. 4).

215 Flow-unit 4 is much more extensive and overlaps all underlying flow-units (Fig. 4). Its outcrop
216 width exceeds 37 km (between Aldea Blanca and Güimar; Figs 1 and 4). Internal entrachrons (marked
217 by appearances and disappearances variously of accretionary lapilli, abundant lithic clasts, and tephri-
218 phonolite pumice) reveal that the distribution of the current gradually increased with time (Fig. 4), and
219 that later parts of the current (Member 9) entered the Güimar valley for the first time during the
220 eruption. The flow-unit is thickest (>35 m) and most complete in central parts of the Bandas del Sur
221 (e.g., La Caleta to Fasnía; Fig. 1). In the west it is generally thinner (<10 m) and only comprises later
222 parts of Flow-unit 4 (Members 6–9) overlying Member 1 pumice and ashfall layers. In the East
223 (Güimar valley, Fig 1) the ignimbrite sheet comprises only the latest parts (Member 9), locally with
224 ashfall and pumice fall layers (Fig. 4). Ignimbrite is absent where the coastal flanks are steeper
225 (between Fasnía and Güimar; Fig. 3).

226 Each ignimbrite flow-unit has an associated thin (cm-thick) co-ignimbrite ash fall layer. These
227 ash layers are predominantly composed of ash pellets. They are more extensive than the ignimbrites,
228 and covered much of the south coast of Tenerife (see Brown and Branney 2004a; Brown et al. 2010).

229

230 **Longitudinal (parallel-to-current) architecture**

231 The Poris ignimbrite sheet is absent on the steeper ($9\text{--}15^\circ$) upper flanks of Cañadas volcano, but is
232 present locally in the caldera wall and on the nearby upper NE flank (Edgar et al. 2002; Smith 2012).
233 More generally, the ignimbrites are preserved on the less steep ($<4^\circ$) slopes of the coastal pyroclastic
234 apron (Fig. 3) within 5 km of the present coastline, but rarely above ~ 200 m altitude. The general
235 absence of ignimbrite on the steeper ($>4^\circ$) slopes cannot be an artefact of subsequent erosion because
236 (1) the enclosing fall deposits extend upslope beyond where the ignimbrites of the lower slopes pinch
237 out; and (2) the architecture of the ignimbrite sheet shows that the original proximal edge of the
238 ignimbrite is preserved on the lower gradient slopes (Fig. 5). The upper surfaces of the ignimbrite sheet
239 generally dip $1\text{--}4^\circ$ seaward, and the sheet pinches out up the broadly concave slope at 300–400 m
240 altitude (Fig. 5).

241 The coastal apron provides excellent continuous 5 km-long longitudinal sections through the
242 Poris ignimbrite sheet. Tracing the individual ignimbrite flow-units and the entrachrons within them in
243 a downcurrent direction (see Fig. 5) has enabled the internal architecture to be reconstructed in a
244 parallel-to-current orientation. This architecture is well illustrated in a ~ 1 km-long continuous section
245 north-west of Montaña Magua (Fig. 5) where three ignimbrite flow-units (1, 2 and 4) are preserved in a
246 current-parallel section both along a fossil interfluvial and along a palaeo-valley. Both along the
247 interfluvial and along the valley axis, successive flow-units onlap in the upcurrent direction against the
248 regional slope (Fig. 5): Flow-unit 1 thins upslope from 2 m to <0.06 m over a distance of ~ 100 m;
249 Flow-unit 2 thins from 15 m to 2 m over the same distance (Fig. 5). Upslope, these flow-units pass into
250 thin ash veneers that are texturally indistinguishable from the veneer deposits that they grade into
251 laterally across palaeo-ridges (Fig. 5).

252 Flow-unit 4 also onlaps against the slope and thins from ~ 35 m (reconstructed thickness, Fig. 5)
253 to 0 m upslope over a distance of <900 m. Entrachrons within it pick out similar internal
254 retrogradational relationships with topography (Members 6-9 on Figs 5 and 6A-C). This onlapping,
255 retrogradational architecture is repeated on a smaller scale producing a giant bedform in Flow-unit 4 at

256 Montaña Magua (Brown and Branney 2004b). Thus, the retrogradational geometry of the flow-units
257 and their internal architectures mirrors the geometry of the entire ignimbrite sheet (Fig. 6D). The
258 proximal edge of the ignimbrite sheet and all units within it have a ‘feather edge’ geometry (Fig. 6D;
259 also exposed in quarry faces at El Arrecife). Similar onlapping retrogradational architectures are also
260 seen in the Abades ignimbrite (Fig. 7F).

261

262 **Tranverse (sideways-to-current) architecture: gradations from valley-fill to veneer facies**

263 Lateral variations from thin veneers of ignimbrite on palaeo-ridges to thicker valley-fill ignimbrite in
264 palaeo-valleys are well preserved. Several near-complete valley cross-sections are exposed at Montaña
265 Magua, and we focus on these (Figs 1 and 7).

266

267 *Flow-units 1 and 2*

268 Near Montaña Magua the lower two flow-units each comprise an ignimbrite overlain by an extensive
269 ash pellet fall layer (Figs. 3 and 7). Flow-unit 1 comprises up to 2.5 m thick, ash-rich yellowish lapilli-
270 tuff with scattered accretionary lapilli. Flow-unit 2 comprises up to 15 m of poorly sorted massive
271 lapilli-tuff, with local clast-supported pumice lenses along the palaeovalley sides. The ignimbrites are
272 thickest in palaeovalleys, where they are lenticular in cross-section and flat topped (Fig. 7A-C). Moulds
273 of small shrubs and current-orientated delicate twigs and grasses are commonly preserved along their
274 bases. Complete gradations from valley-fill to veneer facies are exposed for flow-units 1 and 2 (Fig. 7).
275 The ignimbrite veneers are laterally extensive across palaeo-ridges and are found on slopes as steep as
276 35°. They are typically several centimetres thick and are composed of massive tuff. Diffuse
277 stratification is present at some localities. They locally thicken into shallow topographic depressions.
278 The upper parts of both the valley-fill and veneer ignimbrites contain scattered accretionary lapilli and
279 each ignimbrite flow-unit is overlain by an extensive, thin co-ignimbrite ash fall layer made of ash
280 pellets (Brown and Branney 2004a; Brown et al. 2010; ash pellets are AP1 type of Brown et al. 2012).

281

282 *Flow-unit 4*

283 The lowermost part (Member 6) of Flow-unit 4 is geographically restricted with abundant large
284 accretionary lapilli (Fig. 7). Within palaeovalleys it reaches 12 m thick and is massive. Diffuse bedding
285 gradually appears within upper parts and towards palaeovalley margins, where initially indistinct,
286 bedding gradually becomes more distinct and also more close-spaced, so that the massive valley-fill
287 ignimbrite grades imperceptibly into the thinner, diffuse-stratified veneer facies (Fig. 7; this is ‘splay-
288 and-fade’ stratification of Branney and Kokelaar 2002). The veneer component of Member 6 is
289 complex with rapid lateral variations. It typically comprises a decimetre-thick unit of diffuse-bedded to
290 stratified tuff and accretionary lapilli-rich lapilli-tuff with scattered pumice and lithic lapilli (see Brown
291 et al. 2010; Fig. 7). Discontinuous planar scour surfaces separate beds, which lack accretionary lapilli
292 in their lower portions. Low-angle cross-stratified tuff occurs locally at the base of these beds.
293 Accretionary lapilli (AP2 types of Brown et al., 2012) are 10 times as abundant in the thin topography-
294 draping veneer ignimbrite ($\sim 400\text{--}500/\text{m}^2$) as they are in the coeval thicker, valley-filling ignimbrite
295 ($\leq 50/\text{m}^2$). Elsewhere around Montaña Magua, the veneer ignimbrite exhibits stratification defined by
296 discontinuous lenses and layers of lithic lapilli, pumice lapilli or accretionary lapilli. Small steep-sided
297 scours are also present (see Brown and Branney 2004a).

298 Within Flow-unit 4, Member 6 passes up into Member 7 ignimbrite that lacks accretionary
299 lapilli (Figs. 2 and 7). Within the palaeovalleys, Member 7 is >20 m-thick, homogenous massive
300 lapilli-tuff. Laterally, this passes gradationally across palaeovalley sides into an extensive veneer
301 ignimbrite, typically 2–5 m thick (Fig. 7). Within the veneer of Flow-unit 4, the contact between
302 members 6 and 7 is sharp and marked by a scour surface. At many localities within the veneer, Member
303 7 includes stratified, cross-stratified, diffuse-bedded and massive lapilli-tuff. Subtle, complex vertical
304 grading patterns (normal and inverse) of lithic and pumice lapilli are common. Individual beds and
305 strata are discontinuous over metres to decimetres and it is not possible to trace them between outcrops.
306 Pods, lenses and thin layers of clast-supported pumice or lithic lapilli and blocks are common
307 throughout the veneer facies; in places they exhibit load-and-flame structures, some of which are

308 sheared in a downslope direction. Shallow to steep-sided and poly-phase scours and diffuse low-angle
309 truncations that pass laterally into diffuse-bedding and then fade out laterally into massive lapilli-tuff
310 are common ('scour splay-and-fade stratification' of Branney and Kokelaar 2002). A 9 m long by 0.4
311 m high dune bedform outcrops at Montaña Magua and was described in detail by Brown and Branney
312 (2004b).

313 Member 7 passes up abruptly into Member 8, a widespread coarse-grained, clast-supported
314 lithic-rich grey to pink ignimbrite that reaches 15 m-thick within palaeovalleys (Fig. 7). To the north of
315 Montaña Magua it typically has a preserved thickness of 2–3 m and passes laterally into a 0.3–1 m-
316 thick topography-draping veneer. It lacks the abundant lithic lapilli, blocks and boulders seen
317 elsewhere in this member (see Brown and Branney 2004a). The juvenile pumice changes from highly
318 vesicular phonolite to dense and variably vesicular, banded tephri-phonolite (Brown and Branney
319 2004a). The first appearance of the more mafic juvenile material can be traced throughout the
320 ignimbrite sheet as an entrachron, as can the base of the lithic breccia, marked by the first appearance
321 of abundant quantities of lithic clasts within the flow-unit. Metre-scale scouring of the underlying units
322 has occurred locally (e.g. at Tajao, Fig. 1), but elsewhere the base exhibits spectacular load structures
323 and pods into the underlying Member 7 ignimbrite. Member 8 passes gradationally upwards into
324 Member 9 which is only preserved as a veneer facies pumiceous lapilli-tuff <1 m thick. It is commonly
325 composed of clast-supported pumice lapilli and blocks. Its across-valley geometry and lithofacies
326 transitions are not well constrained.

327 In summary, the ignimbrite flow-units are thick in palaeovalleys and thin over palaeo-ridges
328 (Fig. 7D). The early flow units (1–3) thin markedly over palaeo-ridges, with thickness ratios of the
329 order of 100:1. In contrast, the difference in thickness between coeval ignimbrite in palaeovalleys and
330 palaeoridges in Flow-unit 4 is much less (<5:1; see Fig. 7D).

331

332 **Interactions between density currents and topographic obstacles**

Basaltic scoria cones up to 300 m high pepper the lower flanks of Las Cañadas volcano (see Bryan et al. 1998a; Kröcher and Buchner 2009; Fig. 8A). During explosive eruptions they obstructed PDCs and resulted in the upstream accumulation of anomalously thick sequences of ignimbrite. An instructive example of this can be seen in the Güimar valley (Fig. 1) — an 8 km wide, flat-bottomed scarp formed by catastrophic sector collapse of the SE flank of Tenerife. The PDCs flowed down the Güimar valley, and across two close-spaced scoria cones situated 1.5 km from the present coastline (Fig. 9). Long axes of imbricated tree moulds are aligned parallel to flow direction (towards the SE) and indicate that the current passed over the scoria cones (Fig. 9). However, Flow-unit 4 is anomalously thick between and upstream of the scoria cones: it is predominantly massive and exceeds 13 m in thickness immediately upstream of the northernmost scoria cone (Flow-unit 4, Fig. 9). It then thins to 3–6 m over the upstream sides of the scoria cones (logs B and D on Fig. 9). Yet, on flat ground downstream and laterally away from the cones, the density current apparently did not deposit anything, because the ignimbrite flow unit is absent there and the Poris Formation comprises only the ash fall and pumice fall layers (logs A and E on Fig. 9).

Another example of enhanced deposition of ignimbrite upstream of a cone is seen at the ~100 m-high Fasnía scoria cone (Fig. 8A). Here, massive ignimbrites of the Fasnía Formation exceed 7 m thick on the stoss side of the cone (Fig. 8B) while on the lee side the same ignimbrites are only a few centimetres thick and stratified, and they laterally pass into low-amplitude scour surfaces that cut through underlying pumice fall deposits.

Discussion

Topography affected the extensive, radiating pyroclastic density currents (PDCs) on various different scales. These are discussed below.

Controls on the distribution of pyroclastic density currents

Differences between the distributions of the four ignimbrite flow-units (Fig. 4) are attributed to a combination of: (1) changing eruption dynamics; and (2) simultaneous depositional modification of the topography by the density currents. Although comparison of volume of each flow-unit is precluded by flow into the sea, the field relations strongly suggest that the volumes of the first three density currents were lower than those of the fourth current, resulting in Flow-units 1–3 having narrower geographic distributions. In addition, in-situ shrub moulds along the bases of Flow-units 1–3 indicate that these early currents had lower velocities, in contrast to the larger current that deposited Flow-unit 4, which was not only more laterally extensive and capable of transporting lithic blocks 15–20 km from source, but it also stripped mature forest from upper slopes, leaving widely scattered (allochthonous) tree moulds on the coastal plain. As the Poris eruption progressed, the valley/interfluvial topography on the lower coastal flanks of Tenerife was gradually infilled by ignimbrite and, as a result, the later currents were less valley-confined (Figs. 5–7). We infer that this was the result of increasing overspill of small-volume PDCs from one valley into adjacent valleys.

During deposition of Flow-unit 4 the rapid increase in the geographic footprint of the density current (Fig. 4) is inferred to have resulted from increases in the mass-flux of the eruption (waxing flow) with a consequent increase in the volume of the density current. The rapid and marked lateral advance of the PDC across the region in eastwards and westwards directions, perpendicular to the flow-direction during the deposition of Flow-unit 4 (Fig. 4) also likely resulted from an increase in the volume of the density current during the climactic stages of the eruption. The current increased not only in capacity (the bulk mass of material carried) and spread out more, but its competence also increased, as recorded by the presence of abundant large lithic blocks and boulders in Member 8. Waxing flow, recorded by the upwards-coarsening, seems to have favoured widespread erosion and entrainment as recorded by the allochthonous tree trunks, lenses of locally-derived lithic clasts, and the presence of metre-scale scour surfaces in the deposits in Flow-unit 4 (Brown and Branney 2004a). Proximally, the increased eruptive mass-flux may also have favoured the current overtopping a broader stretch of the Las Cañadas caldera rim (Fig. 1).

384

385 **Influence of regional-scale topography on deposition from PDCs**

386 On a regional scale, deposition from the Poris density currents was strongly controlled by the large-
387 scale morphology of the ignimbrite shield volcano. Geographic zones of contrasting PDC behaviour
388 can be delineated along the southern flanks of Cañadas volcano (Fig. 10). Deposits in the most
389 proximal regions (i.e., intra-caldera 1–5 km from source) are not available for study, but comparison
390 with ancient dissected calderas suggests that thick accumulations of ignimbrite and lithic breccia were
391 deposited from PDCs that were partially contained within caldera walls (e.g., the Ordovician Scafell
392 Caldera, Lake District, Branney and Kokelaar 1994). Proximal parts of the ignimbrite sheet (<5 km
393 from source) are preserved in the present caldera wall and reach 30 m thick, and are considered to have
394 accumulated in a broad valley oriented east-west away from the caldera walls (Smith 2012).

395 In medial zones (>5–15 km from source, Fig. 10) the PDCs flowed away from the caldera down
396 the steep upper flanks of Las Cañadas volcano. We infer from the absence of ignimbrite in these
397 regions that the PDCs bypassed these steep slopes with accumulative to near-uniform flow capacity
398 (e.g., Kneller and Branney 1995) and remained largely non-depositional for most of their passage to the
399 sea.

400 In distal regions (>15 km from source; Fig. 10) the PDCs started to deposit, presumably caused
401 by passage onto the more gentle (<6°) coastal slopes. We infer that the density currents deposited there
402 as a result of depletive flow capacity (e.g., Kneller and Branney 1995); that is, the spatial decelerations
403 incurred by flow across the regional concave slope. This, combined with the depletive effect of slightly
404 divergent (radiating) flow paths around the island reduced the current's capacity to transport its
405 particulate load, promoting deposition as the current encountered gradually less-steep slopes with
406 proximity to the coast (Fig. 1). Similar processes have been demonstrated in laboratory experiments of
407 aqueous density currents (Garcia and Parker 1989; Mulder and Alexander 2001; Kubo 2004), in
408 numerical simulations (Kassem and Imran 2001) and, for example, where PDCs elsewhere crossed
409 breaks-in-slope (e.g., Roobol et al. 1987; Giordano 1998; Macías et al. 1998; Sulpizio et al., 2007,

2010; Sulpizio and Dellino 2008). It is possible that the reduced gradient of the more coastal parts of the pyroclastic apron may have forced the current to undergo a downstream transition from supercritical to subcritical flow (e.g., hydraulic jump; Van Andel and Komar 1969), but this is not a requirement for deposition and is difficult to established from deposits (e.g. Gray et al. 2005). Turbulence can be generated at a hydraulic jump and this may promote substrate erosion and entrainment, and enhanced mixing with the ambient fluid (e.g., Komar 1971).

We note that scours of all scales occur within Flow-unit 4 deposits in areas where there is evidence for bypassing (i.e., the proximal edge of the coastal ignimbrite sheet, see Brown and Branney 2004a). This indicates that at these areas, substantive accelerations were close to neutral (bypassing with neither overall deposition nor erosion; Branney and Kokelaar 2002) such that relative minor fluctuations in the current (such as pulses or passage of eddies or roll waves) would have been sufficient to induce minor, ephemeral erosion and deposition.

The gradient between the caldera and the coast varies around the volcano. For example, locally on the SE flank, and widely around the north flank, the low-gradient coastal apron is absent, with steep slopes extending all the way to the sea (Figs. 1 and 2). Some of the shortest (14 km) and steepest (consistently $>9^\circ$) flanks on the southern side of the island occur between Fasnía and Güimar (Fig. 2). Poris ignimbrites are widely absent in this section, even at the coast. In this sector of Tenerife, the Poris PDCs bypassed all the way to the sea. We can deduce this because the fall deposits are present in the area and Poris ignimbrite is preserved proximally, directly upslope of this region in the Diego Hernandez caldera wall (Edgar et al. 2002; Smith 2012). We infer that the steeper coastal slopes in this region ensured that capacity of the PDCs remained uniform or accumulative and non-depositional all the way to the sea so that left little or no record was left of their passage.

The bypassing behaviour of the Poris PDCs across the flanks of Tenerife indicates that they were autosuspending currents in a near-equilibrium state (neither eroding nor depositing), similar to the behaviour of some turbidity currents in submarine channels (Stevenson et al. 2012). This condition exists where substantial accelerations approximate to zero (fig 1.1 of Branney and Kokelaar 2002), and

436 this, in turn, depends upon the interplay between any changes in mass flux at source (e.g. eruption
437 dynamics) and the particular configuration of the substrate slope. With a steady input at source, spatial
438 changes in slope induce spatial accelerations (accumulative flow) or decelerations (depletive flow) and
439 thus exert a primary control on the current dynamics and on whether the current erodes, bypasses or
440 deposits (e.g., Kneller and Branney 1995; Mulder and Alexander 2001; Brown and Branney 2004b;
441 refs in Sulpizio and Dellino 2008). The gentle slopes of the coastal pyroclastic apron on Tenerife are
442 composed of ignimbrite sheets, and is similar to turbidite fan systems constructed at the mouths of
443 submarine channels. Proximal scour-and-fill basin-facies turbidites deposited near the start of more
444 gentle slopes are inferred to result from currents that alternated between erosion and deposition (e.g.,
445 Kokelaar 1992; Amy et al. 2007) and are, we suggest, analogous to the proximal feather-edge of the
446 coastal Poris ignimbrite sheet.

447 Other ignimbrites in southern Tenerife show similar distributions, thinning and then pinching
448 out up the concave flank, and we suspect that all PDCs on Tenerife behaved in a similar manner to
449 those of the Poris eruption. Given that the Poris PDCs were depositing thick ignimbrite in proximal
450 extracaldera regions, and that runout distance is closely linked to sedimentation (Andrews and Manga
451 2012), we infer that passage down the long and steep slopes inhibited sedimentation in medial reaches
452 and increased the runout distances and the ignimbrite mass-loading on the coastal apron and offshore.

453 The internal onlapping architecture of the Poris ignimbrite sheet (Fig. 6D) means that the bases
454 of the flow-units, and also the base of the ignimbrite sheet as a whole (excluding the fall layers) are
455 diachronous. Each current did not commence deposition at the same time at all localities across the
456 region. Rather, the onset of deposition migrated upcurrent with time during passage of the current and
457 this advance continued until it reached what is now the proximal ‘feather-edge’ of each ignimbrite
458 flow-unit (Fig. 6D). This is particularly well illustrated by Flow-unit 4, which was deposited from a
459 sustained current that experienced several marked changes in the composition of clasts supplied to it
460 through time (e.g., Fig. 5). Entrachrons that enclose compositionally diverse units onlap against the
461 topography.

The complex onlap architecture is illustrated in more detail by the giant regressive bedform in Member 8 (see Brown and Branney 2004b). It resulted from a sustained PDC that was just entering into a region of deposition at that location. The diachronous character of the Poris ignimbrite sheet means that individual vertical sections through the ignimbrite do not record the entire depositional history of the parent PDC—the same holds true for each individual flow-unit. In general, the onlap relationships suggest that a large proportion of the pyroclastic load of the PDCs was deposited at sea: there is a substantial thickness of pyroclastic material offshore southern Tenerife (Bogaard 1998).

The architectural relationships in the Poris ignimbrite sheet resulted from unsteadiness and non-uniformity in sustained density-stratified PDCs, and they are picked out by entrachrons. However, in massive, homogenous ignimbrite sheets, such as are generated during super-eruptions, these relationships may go unrecorded and the changing position of the aggradation surface during the eruption will remain cryptic. Defining and tracing entrachrons in apparently homogeneous large-volume (100–1000 km³), ignimbrite sheets would be useful in understanding their emplacement history, and may provide clues about the durations of sustained PDCs during cataclysmic eruptions. Analysis of smaller-volume zoned ignimbrite sheets with well defined architectures, such as the Poris ignimbrite, can provide critical clues to help in this endeavour.

The interaction of PDCs with local topography

The valley-fill to veneer lithofacies transitions in the Poris Formation ignimbrite flow-units (Fig. 7) record changes in flow-boundary conditions laterally across topography, i.e., flow-boundary non-uniformity. These differences are primarily the result of a density-stratified current interacting with irregular topography (e.g., Valentine 1987; Pittari et al. 2006). Different topographic elevations project into different levels within the current that have differing particle concentrations, turbulence intensities, compositions (e.g., proportions of ash vs. pumice lapilli) and clast-support mechanisms. Thus, the character of the lower flow-boundary zone that developed within the base of the current vary with elevation.

In the lower flow-units (1–3), lateral transitions from thick massive lapilli-tuff (valley-fill facies) to thin tuff (veneer facies; Fig. 7) record deposition from strongly density-stratified pyroclastic currents that transported the majority of their coarse lapilli along valley axes. The thin ignimbrite veneers lack abundant pumice lapilli and indicate that higher levels (metres to tens-of-metres above the base) within the density-stratified current inundated the local topographic highs, but carried predominantly fine ash.

The marked veneer-to-valley-fill transitions in flow-units 1–3, are similar to those documented in the Oruanui ignimbrite, New Zealand (type B deposits of Wilson 2001). The thinness of the Oruanui veneer deposits was attributed to the ‘fluidity’ of the PDCs, helped by the presence of water in the substrate on the palaeo-valley walls (a ‘hot-skillet’ analogy), which is inferred to have promoted the downhill movement of coarse lapilli. However, coarse lapilli are absent in the Poris Formation on the wide, plateau-like interfluves, which suggests that the extensive upper levels of the Poris PDCs that travelled across the broad interfluves transported few coarse lapilli, in contrast to the current’s lower, more concentrated levels that were more channelised along the valleys and evidently contained abundant coarse pumice. Steam-flashing of water in the substrate (Wilson 2001) would widely disrupt bedding, and is not recorded in the basal pumice fall layers of the Poris Formation. Moreover, the nature of the palaeosol and the spacing of in situ fossil shrubs indicate that the Poris deposits were emplaced in a dry desert landscape similar to that of the present day southern coast. The architectural relationships across palaeo-valleys (e.g. near Montaña Magua; Fig 1) allow some constraints to be placed on the thickness of the lowermost, more concentrated pumice lapilli-bearing levels of the currents at valley axes (Fig. 7). The lower, concentrated levels cannot have been thicker than the current depth of palaeovalleys or pumice and lithic lapilli would have been deposited widely upon the interfluves. We thus infer that lower, concentrated and lapilli-bearing levels of most of the density stratified current were probably less than several metres thick.

Insights into flow non-uniformity over topography can be gleaned by using the height in the deposit at which accretionary lapilli appear and disappear as time-lines. Evidence from numerous

514 ignimbrite sheets on Tenerife indicated that accretionary lapilli initially nucleated in the form of small
515 ash pellets within the buoyant atmospheric co-ignimbrite ash plumes (Brown et al. 2010). These pellets
516 fell out into the current over both valleys and topographic highs and were eventually deposited within
517 the ignimbrite. Additional layers of fine ash accreted to the pellets during their passage through the co-
518 ignimbrite-density current system transforming the ash pellets into accretionary lapilli (Brown et al.
519 2010; also see Van Eaton and Wilson 2012). It is known that they fell directly into the lower parts of
520 the Flow-unit 4 current rather than having been carried from proximal locations by the current because,
521 pumice lapilli and lithic lapilli of pneumatic equivalence to the accretionary lapilli are abundant in the
522 valley-fill ignimbrites, but they are absent in the thin ash veneers, which also contain the accretionary
523 lapilli. Clearly, the competence of the current (measure of the largest-size clast a current is able to
524 transport) on interfluves was insufficient to transport lapilli-sized clasts, and yet the veneer ignimbrites
525 nevertheless contain abundant accretionary lapilli. At Montaña Magua, depochrons marking the
526 appearance and disappearance of accretionary lapilli in Flow-unit 4 are ~0.6 m apart in veneer
527 ignimbrite, but they are more than 12 metres apart in adjacent coeval massive valley-fill ignimbrite
528 (Fig. 7). This indicates that depositional aggradation rates were ~20 times greater in the valleys than on
529 the ridges. However, assuming that accretionary lapilli fell out of upper parts of the current into the
530 aggrading ignimbrite across valleys and ridges, then there is a discrepancy between the thickness ratio
531 of valley-fill and veneer ignimbrite (~1:20) and the accretionary lapilli concentration ratio (1:10). This
532 can be accounted for by the common scours in veneer ignimbrite that indicate intermittent erosion.
533 Thus, while ignimbrite was aggrading within valleys, ignimbrite on the interfluves underwent periodic
534 deposition and erosion by the current.

535 The lateral variations in lithofacies between valley-fill and veneer ignimbrites exhibited by later
536 deposited parts of Flow-unit 4 (Members 7–9; Fig. 7D) are considerably less marked than those
537 exhibited by the earlier flow-units. This change was the result of: (A) a reduction in the relief and
538 accommodation space provided by the valleys due to partial filling by the earlier ignimbrite flow-units;
539 and (B) a marked increase in the volume of the fourth PDC. The increase in volume meant that the

540 remaining topographic relief provided by the interfluves between the partly filled valleys failed to
541 penetrate so high into the now thicker current's density-stratification, such that the more concentrated
542 (granular fluid) lower levels of the current flowed more extensively across the interfluves.
543 Nevertheless, particle concentrations in the lower levels of the current on the interfluves were not
544 sufficiently high to entirely suppress turbulence, as recorded by diffuse bedding and stratification in the
545 veneer facies of Member 7, in contrast with the entirely massive fills in the valleys. Conservation of
546 mass requires that lateral spreading of the current across interfluves would affect the concentration-
547 profile of the current at those locations, for example with thinning of the granular-fluid in lowermost
548 levels of the current. Thus, the character of the lower flow-boundary zone of the current may have
549 changed laterally with fluid-escape dominated deposition along the valleys, to form the massive lapilli-
550 tuff at valley axes, and with less steady deposition more affected by granular flow and tractional
551 processes across the interfluves, as recorded by the more variable, variously diffuse-stratified veneers
552 (e.g., Branney and Kokelaar 2002).

553 Similar lateral variations in a large density current are recorded in the ignimbrite sheet of the
554 1991 eruption of Mount Pinatubo, Philippines (Scott et al. 1996), which also inundated radiating
555 valleys and broad interfluves.

556

557 **Depositional records of bypassing currents: sediment traps on the flanks of Las Cañadas volcano**

558 Enhanced deposition from density currents on the stoss-side of topographic obstructions is common
559 (e.g. Bursik and Woods 2000) and results from local decelerations, in some cases accompanied by the
560 development of upstream propagating bores within the blocked, lower parts of density stratified
561 currents (see Bursik and Woods 2000). The local current decelerations (depletive flow) will locally
562 decrease the flow capacity. On southern flanks of Tenerife, thick ignimbrite accumulations developed
563 upstream of scoria cones, which acted as 'sediment traps'. We infer that the high-concentration basal
564 parts of the current were forced to slow, pond and flow around the sides of the cone (e.g., Baines 1995;
565 Bursik and Woods 2000), while higher, less dense and turbulent levels of the current decoupled (sensu

566 Fisher 1995) and flowed across the cone, eroding the substrate, bypassing, or depositing thin ash
567 veneers on the lee side.

568 In the broad Güimar valley, ignimbrite is absent within the Poris Formation on flat ground away
569 from the scoria cones (logs A and E on Fig. 9). Either the Poris PDC did not flow across these regions
570 or it remained non-depositional and bypassed where not blocked by topographic obstacles. However,
571 the local presence of ignimbrite upstream of several scoria cones indicates that the density current
572 accelerated down the steep east-facing scarps of the valley ($>35^\circ$ 1600 m high, Fig. 9) and then fanned
573 out across the valley bottom. Across most of the valley floor the current remained non-depositional
574 (logs A and E on Fig. 9) and passed out to sea. The current here deposited ignimbrite only where it was
575 forced to slow and flow around scoria cones. Bypassing of PDCs over short distances (<5 km) is
576 common on steep-sided composite volcanoes (e.g., Mount Misery, St. Kitts, Robool et al. 1987; Mount
577 Pinatubo, Philippines, Scott et al. 1996; Roccamonfina volcano, Italy, Giordano 1998). Bypassing over
578 greater distances (> 30 km) is rarer but was inferred to have occurred during large-magnitude eruptions
579 such as the Campanian Ignimbrite, Italy (Fisher et al. 1993). During hazard surveys it would seem
580 appropriate to target scoria cones or other traps on potential bypass surfaces in order to search for local
581 ignimbrite accumulations that would record the passage of large currents: this could help construct
582 eruption histories and determine the hazards around large explosive volcanoes.

583

584 **Using longitudinal ignimbrite architecture to understand large-scale eruption dynamics**

585 Longitudinal architectures in ignimbrite sheets are useful for deciphering large-scale eruption dynamics
586 and regional-scale PDC behaviour (De Rita et al. 1998; Branney and Kokelaar 2002). Two conceptual
587 models have been proposed to account for retrogradation architectures in ignimbrite sheets (Branney
588 and Kokelaar 2002): (1) extending aggradation with dual onlap, such as may result from waxing flow,
589 or (2) overall retrogradation, such as may result when runout distance decreases during waning flow
590 (Fig. 11A). In the former model, the geographic area of deposition increases with time, creating onlap
591 architectures in proximal areas mirrored by onlap in more distal areas; and may result from overall

waxing flow. In the latter model, onlap upslope in proximal areas is accompanied by offlap in distal areas as the distal limit of deposition decreases with time, recording a gradual decrease in runout distance with time, such as may occur due to overall waning flow conditions. The distal architecture of the Poris ignimbrite sheet is obscured by the sea, but from subaerial exposures alone it is apparent that neither of these models fits perfectly. This is because the field relations indicate that retrogradation occurred during strongly waxing flow (see Fig. 5, 6 and 11B; see also Brown and Branney 2004b), as indicated by the overall upward-coarsening sequence, from tuff at the base of Flow-unit 1 to lithic breccias high in Flow-unit 4, (thought to record peak flow conditions as the caldera subsided), and also by the overall increase in geographic area covered by the currents with time. The lower flow-units (1-3) are geographically restricted and preserve in-situ fossil shrubs at their bases, whereas Flow-unit 4 is more widespread and contains abundant allochthonous tree trunks and entrained locally-derived lithic clasts, and coarsens upward into an extensive lithic breccia (see Brown and Branney 2004b). These features suggest that the capacity, competence and the dynamic pressure of the current increased with time during the Poris eruption. The lithic breccia high in Flow-unit 4 is a particularly widespread unit and probably records peak flow conditions (Brown and Branney 2004a). Thus, the retrogradational architecture that is widely exhibited within the Poris ignimbrite sheet across southern Tenerife was assembled during predominantly waxing flow conditions.

We propose that where the current flowed onto lower slopes it was critically balanced with respect to deposition: that is, substantive accelerations within the current were close to zero (autosuspension) because the waxing mass-flux of the current was balanced by depletive flow on the gentle concave slope. In this condition even a very small change in topography was sufficient to locally push the current into deposition (substantive deceleration). Thus, rather minor slope-changes induced slight spatial decelerations sufficient to trigger the onset of deposition in a restricted (~50 m reach) depositional zone. Downcurrent of this zone, the slope was unchanged and the current bypassed to the ocean. Soon, however, the location of the minor slope-induced deposition shifted upcurrent because the current now had to flow over the newly formed ≤ 5 m-thick lens of deposit. Downslope of the lens crest

618 the current continued to flow away downslope to the ocean, without depositing (bypassing). The new
619 deposit lens now itself caused the local deceleration (depletive flow) causing the zone of deposition to
620 shift sourceward, depositing a new lens and so on, so that over time (hours) a single, extensive layer
621 (2–5 m thick over interfluves and <20 m thick along valley axes) was gradually assembled
622 retrogradationally during the eruption. As the eruption waxed, new additions to this layer were coarser-
623 grained (e.g. lithic breccia). Thus we infer that the retrogradation exhibited widely by the Poris and
624 other ignimbrite sheets in southern Tenerife resulted from the gentle concave regional slope and not
625 due to waning flow.

626 Rates of deposition on this gentle concave slope remained low when compared with the inferred
627 larger volumes of material that passed by. This is in contrast with more rapid deposition at a marked
628 break-of-slope as described elsewhere where wholesale rapid deposition is caused by abrupt
629 deceleration with or without a hydraulic jump at a steep obstacle or major change in slope. Eventually,
630 as flow peaked the zone of deposition broadened with aggradation of a new layer of lithic breccia
631 overlapping the earlier retrogradational components of the sheet (Fig. 11C). Locally, the peak waxing
632 phase was sufficient to cause erosion and entrainment of just-deposited ignimbrite, stripping up to 4 m
633 of just-deposited ignimbrites).

634 The presence of a widespread clast-supported pumice-rich ignimbrite (Member 9, Fig. 3)
635 capping Flow-unit 4 is consistent with retrogradation of the ignimbrite sheet, this time as the eruption
636 waned after the caldera-collapse climax. These pumice concentrations are thought to have formed when
637 buoyant large pumice clasts overpassed to become deposited near the distal limits of the current,
638 leaving typical clast-supported pumice-accumulations (snouts and levees). During the sustained
639 current's waning, the distal limits of the current retracted sourceward (retrogradation), producing a
640 strand-line of pumice deposits preserved in uppermost parts of the resultant ignimbrite sheet. This
641 mechanism accounts for upper pumice concentrations in zoned ignimbrites elsewhere (e.g. Zaragoza
642 ignimbrite, Carrasco-Nuñez and Branney 2005). The last upslope lens deposited during final waning
643 stages of the current left a 2-m high dam that after the eruption collected water forming a small lake in

644 which 2 m of pumiceous sediments accumulated (Branney and Brown 2004a), showing that the
645 upslope limit of the present ignimbrite sheet represents the true preserved original limit, not an eroded
646 remnant.

647 In summary, the longitudinal retrogradational architecture of the onshore Poris ignimbrite sheet
648 (see Fig. 11C) resulted primarily from the gently concave regional slope, and occurred during both
649 overall waxing flow conditions (coarsening upwards) and during late-stage waning flow conditions
650 (recorded by upper lithic-poor pumice accumulations). As the last, more prolonged current waxed to
651 the climactic phase, earlier-deposited parts of the ignimbrite were locally stripped out by vigorous
652 erosion, and during the climactic phase of the current (as the caldera collapsed; Brown and Branney
653 2004a) a second layer of ignimbrite was widely assembled above the earlier, retrogradational part of
654 the ignimbrite. This layer was characterised by widespread lithic breccias.

655

656 **Conclusions**

657 Cryptic internal architectures within an extensive ignimbrite sheet on Tenerife have revealed how
658 conditions within a widespread, sustained PDC varied spatially (due to the influence of the regional
659 slope and local valleys and obstacles) and with time (as a result of changing eruption dynamics and
660 modification of topography by deposition). During a large Plinian eruption four widespread, sustained
661 pyroclastic density currents swept down the broadly concave flanks of Las Cañadas volcano.

662 (1) The overall gentle concavity of the volcano's flanks controlled where the currents deposited on
663 a regional scale. The currents bypassed the steeper upper flanks and began to deposit as the
664 slopes gradually decreased with proximity to the coast, more than 15 km from the source
665 caldera. Deposition occurred during both waxing and waning flow periods, and so is inferred to
666 have resulted predominantly from topography-induced spatial deceleration (depletive flow)
667 caused by the combination of slightly divergent flow (flow-paths fanning out) and passage onto
668 lower gradients.

- (2) Bypassing (flow without deposition) characterised PDC behaviour for the majority of the runout distance. The flanks of Cañadas volcano behaved as a broad ‘chute’ or bypass surface, conveying most of the erupted material to the ocean, more than 15 km from source. Such PDC behaviour has two consequences: (A) the volume of the ignimbrite eruptions on Tenerife is difficult to estimate because the bulk of the material resides offshore, so eruption volumes far exceed the volumes of onshore deposits; and (B) it is liable to lead to under-estimates of the number of hazardous density currents to have passed across a volcano flank, because such currents widely leave no depositional record of their passage. Thus, to estimate the true number of density currents that have crossed an area requires careful piecing-together of incomplete information from scattered patches of deposit. This is unlikely to be achieved where exposure is less superlative than is the case in the southern Tenerife desert.
- (3) The prolonged nature (and hence large volume) of a pyroclastic density current that was sustained, for example, throughout the entire duration of a caldera-collapse phase of a large explosive eruption (e.g. Poris Flow-unit 4) may not be immediately apparent from a deceptively thin ignimbrite flow-unit. The thinness of the ignimbrite on a gently concave volcano flank is the result of limited accommodation space (topography), not the duration or size of the current, which may have been prolonged. At any one location deposition occurred during just a fraction of the flow’s duration across that location.
- (4) On gently concave slopes, ignimbrite flow-units were assembled incrementally by upslope advance of the deposit’s source-facing feather-edge. The deposition was diachronous, and the resultant retrogradational onlap architecture within the ignimbrite flow-unit is developed both within the valley fills and in the thin ignimbrite veneers. However, whereas in the veneers, this architecture can be apparent from diffuse-bedding with low-angle backset-type geometry, the same architecture can be entirely cryptic within massive, thicker valley-filling ignimbrite, and only revealed there by analysis of the compositional zoning.

- (5) Local obstacles, such as scoria cones on the bypass surface acted as sediment traps by inducing local depletive conditions with consequent localised deposition of ignimbrite from currents that left little record elsewhere. When attempting fieldwork reconstructions of the PDC history of a large explosive volcano, targeting of stoss sides of scoria cones for investigation is a rewarding strategy
- (6) Deposition of ignimbrite by a sustained PDC modifies the substrate topography sufficiently rapidly to alter the current's spatial patterns of deposition and erosion. In hazard models that predict density current dispersals, assumptions of a constant (e.g. DEM) topography during an eruption may yield misleading results in the case of sustained currents.
- (7) The Poris PDCs were concentrated (granular-fluid based) and density-stratified, as revealed by the field relations across the margins of flow-parallel valleys. Lower, granular-fluid levels of the earlier, smaller currents were largely channelled within pre-existing valleys, whereas higher, more dilute levels spilled widely across extensive interfluves, leaving finer-grained veneers. In contrast, the larger current that deposited Flow-unit 4 flowed across a landscape in which topographic irregularities had been substantially dampened by deposition of ignimbrite from the earlier PDCs. The lower, granular-fluid levels of this current flowed widely across both valleys and interfluves, although the competence of the current to transport large clasts was somewhat higher along valley axes than it was along the elevated interfluves. This PDC was sustained before, during, and after the climactic caldera collapse phase of the eruption, and its grainsize variations record the waxing flow, peak flow, and waning flow conditions. Topography-induced depletive flow was locally sufficiently marked to induce deposition even during the initial phase of waxing flow. However, at several locations the current eroded and entrained several metres thickness of loose ignimbrite deposited by the same current earlier during its waxing phase. This widespread removal of lower parts of Flow-unit 4 means that many sections are incomplete, and record just peak flow and subsequent phases of the current.

719 The presented data illustrate how variations in PDC dispersal, onlapping relationships, diachronous
720 surfaces, bypassing and the waxing and waning of individual currents and of the eruption overall mean
721 that any single vertical section through an ignimbrite sheet may record just a fraction of the complete
722 eruption sequence. Failure to recognise this during hazard assessments may lead to under-estimations
723 of PDC volumes, dispersals and frequencies. This may be most critical on ocean island volcanoes
724 where subaerial flanks act as bypass surfaces across which the PCDs convey the majority of their load
725 into the sea. However, where exposure is sufficient, and by targeting local sediment traps such as stoss
726 sides of scoria cones, more complete flow-histories can be carefully pieced together from patchy
727 deposits, particularly where reconstructions are aided by compositional zoning of the ignimbrite.

728

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733

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Figure Captions

Figure 1. Map of south Tenerife with the major outcrops of the Poris Formation marked. Delineated areas refer to regions referred to in later figures. DEM from GRAFCAN (www.grafcan.es).

Figure 2. DEM of Tenerife shaded for slope angle. Note the crescent-shaped region of low gradient slopes along the southern coast where most of the Poris ignimbrites were deposited (the Bandas del Sur region). Inset shows representative slope profiles as marked on map.

Figure 3. Generalised and composite vertical section of the Poris Formation as exposed along the southern coast of Tenerife with summary of the main characteristics of the members. Taken from Brown and Branney (2004b). L – lapillistone; LT – lapilli tuff; acc – accretionary lapilli; pel - ash pellets; p – pumice-rich; l – lithic-rich; m – massive; db – diffuse-bedded; s – stratified; xs – cross-stratified. See Brown and Branney (2004b) for a full description of members and lithofacies.

Figure 4. Distribution of ignimbrite flow-units across the southern flank of Tenerife. Representative measured sections through the Poris Formation illustrating the distribution and thickness variations of flow-units. Inset DEM of Tenerife showing the minimum areas of the island inundated by successive PDCs. The dispersal of PDCs increased with time during the eruption. Cartoon illustrating the dispersal of the four flow-units in the Poris Formation (see Fig. 1 for localities).

1078 **Figure 5.** Parallel-to-current architecture of the Poris ignimbrite sheet at Montaña Magua (Fig. 1).
1079 Measured sections through the ignimbrite sheet indicate that the flow-units, and members in Flow-unit
1080 4, pinch-out upslope against the substrate. Thus the base of the ignimbrite sheet is diachronous. Logs
1081 compressed for clarity: inset shows the location of measured sections and a restored longitudinal cross-
1082 section through the ignimbrite sheet.

1083

1084 **Figure 6.** Longitudinal architecture of the Poris ignimbrite sheet around Montaña Magua (see Fig 1 and
1085 inset in Fig 5). A) View downcurrent of Member 8 (Flow-unit 4) which onlaps upstream against the
1086 topographic slope (UTM: 357661/3119160). Member 7 (also of Flow-unit 4) in distance and preserved
1087 in small topographic depressions (arrowed). B) Member 7 pinching out upslope (UTM:
1088 357945/3119059). C) Opposite side of valley to B. Bedding within Member 7 ignimbrite pinching out
1089 against the topographic slope. Current is from left to right. D) Lens of Member 9 ignimbrite overlain by
1090 volcanoclastic sands and gravels that were deposited against the upstream-dipping surface of the
1091 ignimbrite sheet. E) Member 8 lithic breccia forming the proximal feather edge of the ignimbrite sheet
1092 at El Arrecife. All lower units have pinched out further downslope. Current oblique out of page, left to
1093 right (UTM: 357654/3117857). F) Block diagram illustrating the reconstructed architecture of the
1094 ignimbrite sheet as based on outcrops around Montaña Magua (see Figs 5 and 7). Note the onlapping
1095 relationships of successive units and the retro-gradational, back-stepping architecture. F) Parallel-to-
1096 current section through the Abades ignimbrite showing onlapping of lithic-bearing layers (dashed lines)
1097 against the palaeoslope (arrowed). The base of the ignimbrite sheet is diachronous.

1098

1099 **Figure 7.** Representative logs at Montaña Magua through the ignimbrite sheet in veneer, valley-margin
1100 and valley-fill locations (for location see inset, Fig. 5). A) Panoramic view of spectacular palaeo-
1101 valley-filling ignimbrites. View to north and current out of page. Palaeo-valley axis runs out of the
1102 centre of the page (see inset in Fig. 5 for location). B) Close-up of northern valley-fill in B showing
1103 transition from valley-filling facies to veneer facies. Position of logs in A is indicated. Note that these

1104 outcrops are being progressively covered by bulldozed rubble from adjacent construction work. C)
 1105 Close-up of southern valley-fill in B showing abrupt pinch-out of valley-fill facies in Flow-unit 2.
 1106 Flow-unit 2 was largely confined within the valley. D) Cartoon showing reconstructed transverse-to-
 1107 current architecture across a palaeo-valley. Lithofacies as in Fig. 1 and Brown and Branney (2004b).
 1108
 1109 **Figure 8.** Interaction of PDCs with scoria cones on the southern flank of Tenerife. A) Photo of the
 1110 Fasnía scoria cone (Fig. 1; UTM 359476/3123344), which has an anomalously stoss-side accumulation
 1111 of Fasnía Formation ignimbrite; lee side is mantled by coeval thin ignimbrites and fall deposits. B)
 1112 Anomalously thick ignimbrite on stoss side of Fasnía cone.
 1113
 1114 **Figure 9.** The interaction of PDCs and scoria cones in the Poris Formation. A) Measured sections
 1115 through the Poris ignimbrite sheet in the Güimar valley (see inset for localities). Ignimbrite sheet is
 1116 composed mostly of Flow-unit 4, which is thickest immediately upstream of the scoria cones, but is
 1117 absent in localities away from the cones. PDCs generated in Las Cañadas caldera flowed into the
 1118 Güimar valley on their way to the sea. Insets show location of sections. Aerial photograph 2011 Google
 1119 ©.
 1120
 1121 **Figure 10.** Cartoon illustrating the different depositional regimes developed as PDCs disperse away
 1122 from Las Cañadas caldera on Tenerife. In intra-caldera settings high ignimbrite accumulation rates
 1123 resulted from topographic reflection and obstruction of PDCs by the growing caldera wall (A). In
 1124 immediate extracaldera settings parts of the PDC that escaped the caldera rapidly sedimented thick
 1125 ignimbrite over flat ground (B; see Smith and Kokelaar submitted). As the currents accelerated down
 1126 the steep upper flanks of the flanks of the volcano they entered into an accumulative capacity and
 1127 started to erode the substrate (C). They were effectively in a bypassing regime. Ignimbrite was not
 1128 deposited except where parts of the current were obstructed by scoria cones (D). As they reached the
 1129 lower flanks the currents passed onto lower gradient slopes, decelerated and entered into a depletive

capacity. This may have coincided with a hydraulic jump in the current. Loss of capacity resulted in ignimbrite deposition. The transition from a bypassing regime into a depositional regime is marked in the deposit by abundant stratification and scours within the deposit (E). Deceleration across the coastal flanks and out into the ocean resulted in rapid sedimentation rates (F).

Figure 11. Conceptual models for the architecture of the Poris ignimbrite sheet on the southern flank of Tenerife and interpretations of the gross eruption dynamics (following Branney and Kokelaar 2002). A) Two possible models to explain the genesis of the observed retrogradational, onlapping architecture of the proximal edge of the Ignimbrite sheet: extending aggradation with dual onlap (waxing mass-flux) or retrogradation (strongly waning flow). B) Cartoon qualitatively illustrating the changing mass flux of the Poris PDCs as deduced from lithological evidence in the ignimbrites. C) Preferred interpretation of the Poris ignimbrite sheet as inferred from both architecture and from lithological evidence—extending aggradational with dual onlap followed by retrogradation architecture resulted from an initial intermittent but low volume that increased rapidly during the eruption before strongly waning.

A Extending aggradation with dual onlap - waxing mass-flux

Retrogradation - strongly waning flow

B

Flow-unit 4

waning flow

- thin pumice-rich veneer deposits
- normally-graded lithic clasts

peak intensity

- widespread deposition across whole of Bandas del Sur
- thick valley-fill facies and coarse veneer facies
- abundant lithic cobbles, blocks and boulders and tree trunks

waxing flow

- widespread deposition across whole of Bandas del Sur
- thick valley-fill facies and coarse veneer facies
- increase in transported tree trunks and branches
- common scours up to several metres deep
- upwards increase in lithic content

initial flow

- ribbon-like deposit of valley-confined current
- thin fine-grained veneer deposits

Flow-units 1-3

- ribbon-like deposits of valley-confined currents with thin ash veneer deposits
- in-situ shrub moulds at bases of ignimbrites

C Inferred schematic architecture of the Poris ignimbrite sheet

no ignimbrite deposited here