GEOLOGY | THE GEOLOGICAL SOCIETY OF AMERICA®

https://doi.org/10.1130/G50169.1

Manuscript received 28 February 2022
Revised manuscript received 17 May 2022
Manuscript accepted 22 May 2022

Published online 2 August 2022



# Simultaneous fall and flow during pyroclastic eruptions: A novel proximal hybrid facies

Natasha Dowey[1] and Rebecca Williams[2]
[1]Department of the Natural and Built Environment, Sheffield Hallam University, Sheffield S1 1WB, UK
[2]Department of Geography, Geology and Environment, University of Hull, Hull HU6 7RX, UK

## ABSTRACT

**The deposits of Plinian and subplinian eruptions provide critical insights into past volcanic events and inform numerical models that aim to mitigate against future hazards. However, pyroclastic deposits are often considered from either a fallout or pyroclastic density current (PDC) perspective, with little attention given to facies exhibiting characteristics of both processes. Such hybrid units may be created where fallout and PDCs act simultaneously, where a transitional phase between the two occurs, and/or due to reworking. This study presents analysis of a novel hybrid pyroclastic lithofacies found on Tenerife (Canary Islands) and Pantelleria (Italy). The coarse pumice block facies has an openwork texture and correlates with distal Plinian units, but it is cross-stratified and relatively poorly sorted with an erosional base. The facies is proposed to record the simultaneous interaction of very proximal fallout and turbulent PDCs, and it reveals a fuller spectrum of hybrid deposition than previously reported. This work highlights the importance of recognizing hybrid deposition both in the rock record and in hazard modeling.**

## INTRODUCTION

Analysis of pyroclastic stratigraphy can reveal the behavior and magnitude of explosive eruptions (e.g., Fisher and Schmincke, 1984), providing input parameters for numerical models (e.g., Pyle, 1989; Bursik and Woods, 1996; Doyle et al., 2010) and informing hazard analysis (e.g., Bonadonna et al., 2005). Pyroclastic deposits may be interpreted to record either plume (fallout) or pyroclastic density current (lateral) activity. However, during an eruption, multiple processes related to the eruption column, fountaining, and pyroclastic density currents (PDCs) may impact the same location at the same time. Deposits that capture simultaneous processes are common at tuff cones and maars (e.g., Cole et al., 2001; Zanon et al., 2009, and references therein), but there are relatively few studies of such hybrid deposits formed during Plinian eruptions (e.g., Valentine and Giannetti, 1995). In this study, we (1) disentangled hybrid lithofacies using previously reported examples, (2) defined a new proximal hybrid lithofacies based on evidence from the 273 ka Poris Formation of Tenerife (Canary Islands) and the 46 ka Green Tuff of Pantelleria (Italy), and (3) considered its significance for interpretation and modeling of volcanic hazards.

## HYBRID LITHOFACIES

Deposits classified here as hybrid exhibit characteristics of both Plinian fallout (typically clast-supported and landscape-mantling deposits; e.g., Walker, 1971) and ignimbrite deposited by PDCs (typically ash- and pumice-rich deposits that are poorly sorted; e.g., Fisher and Schmincke, 1984). Hybrid facies can vary in appearance; ignimbrite stratigraphy varies dependent on a range of factors (such as PDC concentration, on a spectrum of fully dilute to fully concentrated; e.g., Branney and Kokelaar, 2002; Sulpizio et al., 2014), and Plinian fallout units are variable due to factors including plume height and proximity to the vent (e.g., Cioni et al., 2015).

### Simultaneous Primary Deposition

Valentine and Giannetti (1995) described a hybrid lithofacies generated by primary volcanic fallout and PDC processes operating simultaneously within the White Trachytic Tuff at Roccamonfina, Italy (subunit $E_1$). Associated ignimbrite is predominantly fine-grained ash, with minor pumice lapilli. By contrast, the hybrid lithofacies is clast-supported and consists of angular pumices ranging from coarse lapilli to small blocks. Pumice layers grade from ignimbrite, thicken and thin, and pinch out laterally. The hybrid lithofacies is interpreted to record Plinian fallout into dilute (ash-rich) PDCs that waxed and waned; the pumice-fall was either incorporated into the currents or fell through them and dominated the deposition.

### Alternating Primary Deposition

Alternating PDC and fallout units in volcanic successions may be interpreted as hybrid facies. A spectrum of lithofacies architecture can occur at the base of ignimbrite successions, marking the change from Plinian fallout to PDC deposition (for a review, see Valentine et al., 2019). Modeling has been used to propose that a "transitional regime" can occur between the two end members where the collapsing eruption column is oscillatory and highly unsteady (e.g., Neri and Dobran, 1994; Di Muro et al., 2004, and references therein). Di Muro et al. (2008) described a hybrid lithofacies recording this transitional regime in the 800 yr B.P. Quilotoa succession in Ecuador. The A2 submember of unit U1 is composed of alternating clast-supported pumice lapilli layers and beds of stratified ash, pumice, and lithic lapilli. Proximally, the facies is cross-stratified. Distally, regressive and progressive bed forms occur, and the facies grades laterally into a pumice lapilli bed.

Alternating facies in the 1912 CE Novarupta proximal succession (Alaska, USA), were interpreted by Houghton et al. (2004) to reflect coeval regimes rather than plume oscillation. Unit Fall 2/PDC 2, comprising up to seven PDC beds with thin intervening lapilli falls, was proposed to record fallout deposited during intervals between discrete PDC units from a plume that maintained buoyant and nonbuoyant states simultaneously.

### Reworking and Redeposition

Deposits that exhibit characteristics of both fallout and PDC processes may be created by reworking. Fallout units can be reworked by

CITATION: Dowey, N., and Williams, R., 2022, Simultaneous fall and flow during pyroclastic eruptions: A novel proximal hybrid facies: Geology, v. XX, p. , https://doi.org/10.1130/G50169.1

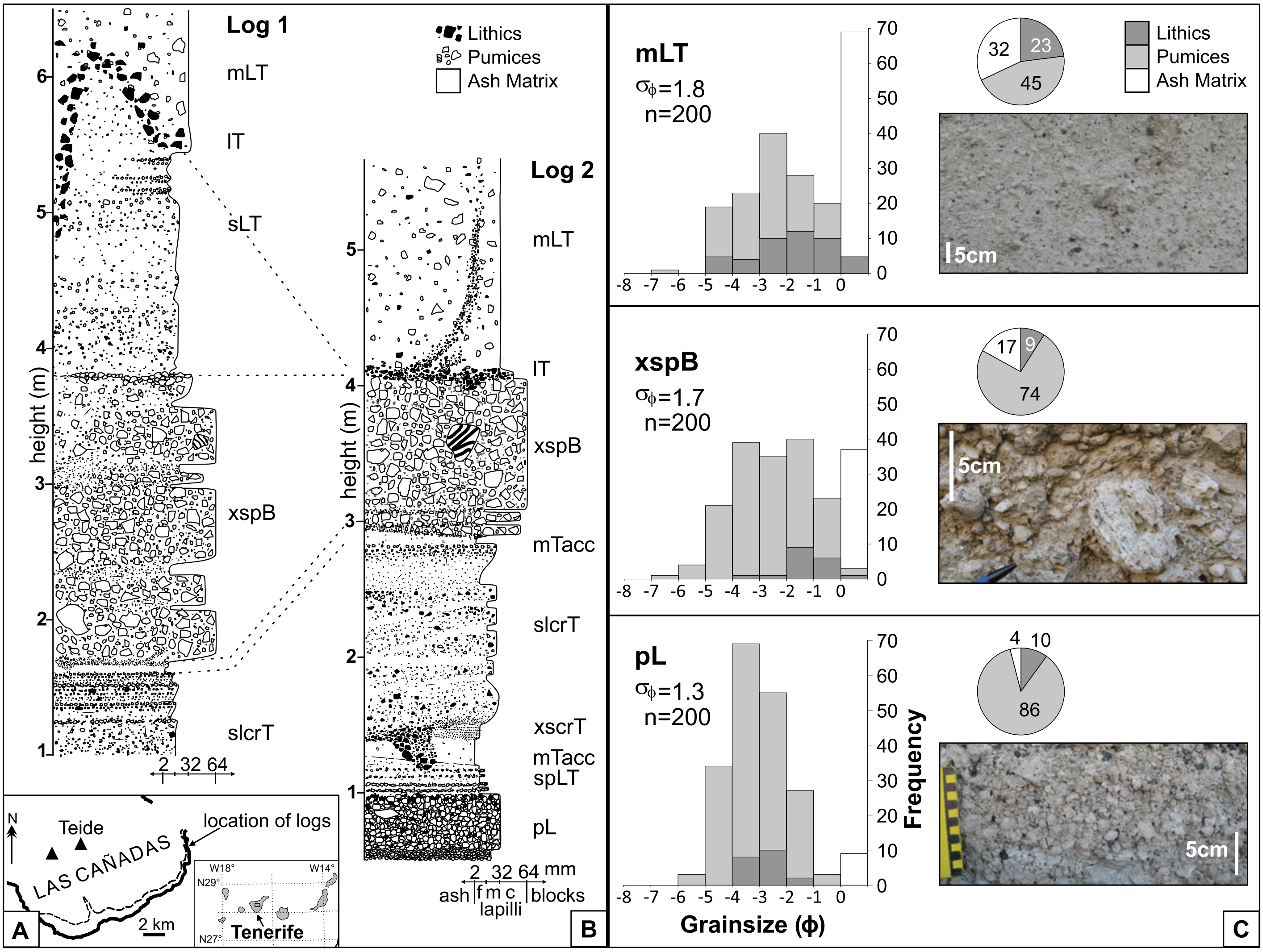


**Figure 1. The xspB facies, Tenerife, Canary Islands. (A) Location, and (B) stratigraphic logs 20 m apart at 28.280273°N, 16.549526°W. Facies abbreviation key is shown in Figure 3. (C) Grainsize distribution histograms and pie charts illustrating comparative grain size, sorting, and componentry (see the Supplemental Material[1]).**

ambient wind or water during a hiatus in the eruption (e.g., Yellowstone, USA; Myers et al., 2016). The syneruptive involvement of strong wind currents may create a lack of clear distinction between the deposits of Plinian fallout and a fully dilute PDC (Wilson and Houghton, 2000). Wilson and Hildreth (1998) described a hybrid fall deposit in the Bishop Tuff, California, distinguished by variable cross-bedding and the presence of subrounded pumice lapilli, which was interpreted to record redeposition of Plinian fallout by wind vortices driven by air currents into coeval PDCs.

## NEW HYBRID LITHOFACIES

Investigations of proximal pyroclastic stratigraphy are rare, in large part because of non-preservation due to caldera collapse or erosion during eruption waxing. However, where preserved, proximal exposures can give important insights into complex depositional processes (e.g., Druitt and Sparks, 1982; Houghton et al., 2004). We report a proximal hybrid lithofacies (referred to throughout as xspB) found at Las Cañadas caldera (Tenerife), and at Pantelleria.

### Poris Formation, Tenerife

Proximal deposits of the 273 ka Poris eruption are exposed at Las Cañadas less than 4 km from the likely vent location, in the 1.9-km-wide Diego Hernandez wall (Smith and Kokelaar, 2013; Fig. 1A). Distal Poris exposures occur 15–20 km away in the coastal Bandas del Sur (e.g., Brown and Branney, 2004).

The proximal Poris Formation includes a parallel-stratified to cross-stratified pumice-block facies (xspB; Fig. 1B). Typically <2 m thick, xspB consists of pumice-rich beds 50–800 mm thick bounded by ash-rich beds <100 mm thick (Smith and Kokelaar, 2013). Pumice beds are poorly sorted ($\sigma_\Phi = 1.7$; see Figure 1C for grain-size distribution) and typically contain 70%–80% pumice lapilli and blocks (5–300 mm) with rare lithic lapilli. At one location, a pumice bed is fully clast-supported (Fig. 2A). Pumices ~20 mm in diameter are subrounded, while large lapilli and blocks (20–300 mm) are subangular to angular. Pumice blocks show no evidence of ballistic impact (such as sag structures or jigsaw-fit breakage). Pumice beds display planar and low-angle cross-stratification (Fig. 1B) and occasional internal cross-stratification of pumice clasts (Fig. 2B). Three-dimensional cuts show that xspB beds thin and thicken both laterally and longitudinally. The xspB facies is in gradational to erosive contact with stratified lithic-rich lapilli-tuff below, and it is overlain by stratified to massive lapilli-tuff with a locally erosive contact (Fig. 1B). It is poorer in ash and lithic content (by 15% and 14%, respectively, at Figure 1 locality) and better sorted than the massive lapilli-tuff. The xspB facies is distinct from bedded pumice lapilli

[1]Supplemental Material. Methods and imagery. Please visit https://doi.org/10.1130/GEOL.S.20247288 to access the supplemental material, and contact editing@geosociety.org with any questions.

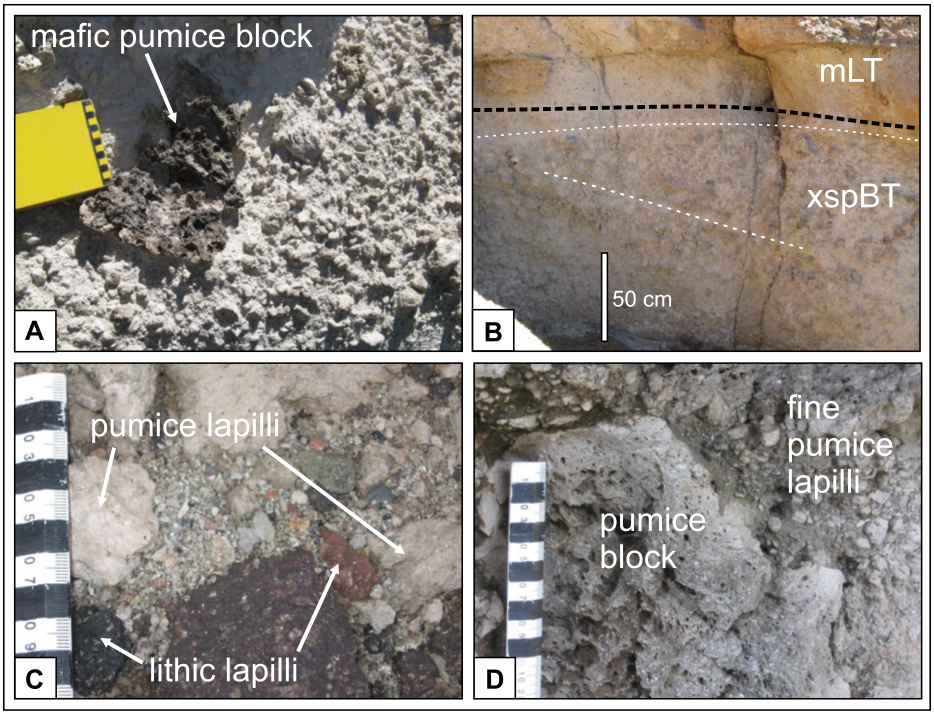


**Figure 2. The xspB facies at Tenerife, Canary Islands. (A) Clast-supported deposit with phonotephrite pumice block (28.270853°N, 16.545632°W); (B) Deposit exhibiting internal cross-stratification (28.267141°N, 16.546145°W) and Pantelleria, Italy (36.819358°N, 11.988439°W). (C) Poorly sorted polylithic-rich lens. (D) Coarse pumice blocks alongside more rounded pumice lapilli (scale in 10 mm).**

at the base of the succession by the pumice blocks (Fig, 2A), poorer sorting ($\sigma_\Phi = 1.7$ vs. $\sigma_\Phi = 1.3$; Fig. 1C), cross-stratification, and variable ash content (Fig. 1B).

In distal Poris Formation exposures, two discrete clast-supported pumice lapilli facies record Plinian fallout (members 1 and 5 of Brown and Branney [2013]). The proximal xspB facies stratigraphically correlates with the upper distal fallout (Smith, 2012).

**Green Tuff Formation, Pantelleria**

The 46 ka Green Tuff Formation is well exposed across Pantelleria, from the Cinque Denti caldera walls (<3 km from the vent) to coastal sections (<7 km from the vent; Williams, 2010; Williams et al., 2014). In the Cinque Denti wall at Bagno dell'Acqua (Fig. 3A), the proximal Green Tuff Formation contains discontinuous horizons of a clast-supported, poorly sorted ($\sigma_\Phi = 1.6$; Figs. 3B and 3C), cross-stratified, pumice-block facies (xspB). The facies consists of angular pumice lapilli and blocks (<275 mm) and subordinate polylithic lapilli and blocks (<77 mm; Fig. 2C) that are not systematically smaller than pumice clasts. Local lithic- and pumice-rich lenses (Fig. 2D) occur within the unit. Cross-stratification in xspB is relatively high angle (~20° to 30°), not unidirectional and transverse to the inferred current direction. Locally, lithic-rich scours <300 mm thick and <500 mm wide, with >40% lithics, occur at the base of xspB, with basal contacts cutting into the units below (Fig. 3B).

The xspB facies grades vertically from a massive pumice lapilli facies with a locally erosive contact; xspB is distinct from the underlying unit in that it contains larger pumice and lithic blocks and exhibits poorer sorting (Fig. 3C), has a wider range of lithic clast compositions, and is cross-stratified. It correlates compositionally (Zr ppm) and stratigraphically with a pumice

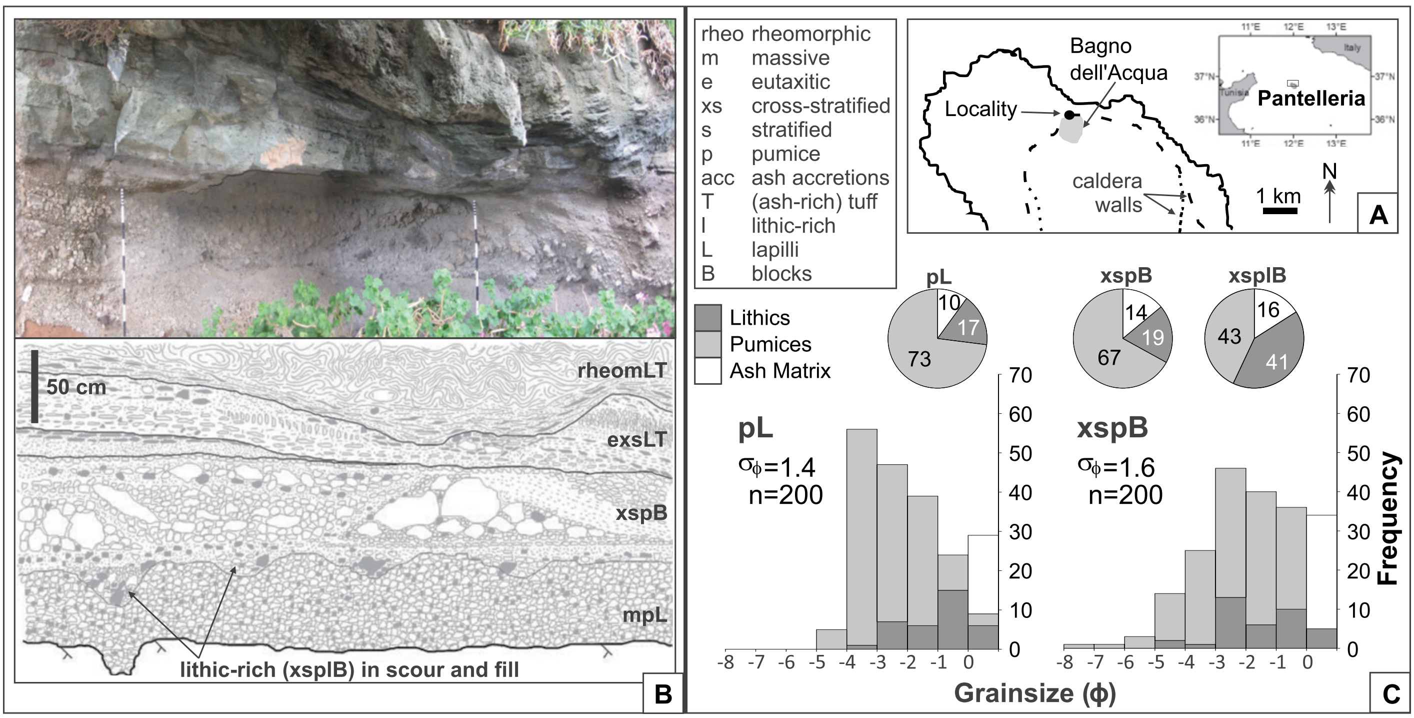


**Figure 3. The xspB facies, Pantelleria, Italy. (A) Location map (36.819358°N, 11.988439°W). (B) Photo panel depicting xspB atop pumice lapillistone and overlain by eutaxitic, cross-stratified lapilli-tuff. (C) Facies key, grain-size distribution histograms and componentry pie charts (see the Supplemental Material [see footnote 1]).**

(or ash) fall layer in coastal sections (Williams et al., 2014). The overlying facies is welded ignimbrite.

## INTERPRETATION

The xspB facies differs from proximal lithic-rich breccias (e.g., Druitt and Sparks, 1982). It is dominated by pumice (with the exception of minor lithic-rich lenses at Pantelleria), does not contain grading or elutriation pipes, and does not grade laterally into ignimbrite. The xspB facies has similarities to fines-poor ignimbrite (e.g., Walker et al., 1980); it is better sorted and coarser than massive lapilli-tuff, and it is less well-sorted than associated Plinian deposits. However, xspB is not massive, does not occur just locally (at Tenerife, it is continuous across the caldera wall), and correlates laterally with Plinian fallout. The cross-stratification makes xspB distinct from reported proximal fallout, such as the coarse, poorly sorted "Bed S" of the 1912 Novarupta eruption, which records complex fallout from a "collar" of low-fountaining ejecta (Fierstein et al., 1997). However, like Bed S, xspB contains distinctly coarse and poorly sorted pumice blocks.

The xspB facies exhibits characteristics of both fallout and PDC deposits. The subangular pumice blocks, areal continuity, (variable) open-work texture, and correlation with Plinian units are suggestive of fallout (e.g., Walker, 1971). The cross-stratification, relatively poor sorting, erosional base, and lack of aerodynamic equivalence between adjacent clasts suggest PDC deposition (e.g., Branney and Kokelaar, 2002). The xspB facies differs from previously reported hybrid facies. It has a different grain size compared to associated Plinian fallout (Figs. 1B and 3B), and at Pantelleria, it displays higher-angle cross-stratification than the hybrid facies created by fallout into dilute PDCs described by Valentine and Giannetti (1995). It does not always directly overlie Plinian fallout facies (Tenerife), nor does it contain interbedded strata (cf. Di Muro et al., 2008). However, the dominance of pumice blocks is akin to the coarse proximal fallout layers in the alternating Fall 2/PDC 2 sequence at Novarupta (Houghton et al., 2004). The xspB facies is interpreted to record primary volcanic deposition; the proximal location makes extensive aqueous reworking unlikely, as there is no catchment or upslope source of water. The componentry of xspB differs to underlying and coeval pumice-fall deposits, making clear-air reworking of those facies unlikely (cf. Wilson and Hildreth, 1998).

At Tenerife and Pantelleria, the increase in grain size in xspB relative to underlying facies records an influx of coarser material at the vent. This may be due to vent widening and shallower fragmentation (evidenced by coarse lithics within the lithofacies at Pantelleria and underlying lithic-rich stratified tuff at Tenerife; Smith and Kokelaar, 2013). As coarse material entered the column, large blocks would have been deposited from a low-fountaining collar of fallout ejecta (as invoked by Fierstein et al. [1997]), and smaller material would have been transported in PDCs formed by contemporaneous fountaining.

In the Poris eruption, PDC activity had begun prior to deposition of xspB (recorded in underlying tuff deposits; Brown and Branney, 2004; Smith and Kokelaar, 2013), but it was unsteady and marked by waxing and waning that led to changes in runout distance. During deposition of the xspB facies (~4 km from likely vent), a hiatus in distal PDC activity allowed contemporaneous Plinian fallout to be recorded at the coast (Dowey et al., 2020). On Pantelleria, xspB marks the onset of PDC activity, indicating that the vent widening episode may have instigated column collapse. The proximal currents did not travel far (<1 km); xspB is not longitudinally extensive and is absent at distal locations.

The xspB facies reported here contains predominantly coarse material with variable fines, and it exhibits cross-stratification. Cross-stratification indicates traction-dominated deposition and migration of bed forms at the flow-boundary zone (sensu Branney and Kokelaar, 2002). This has typically been associated with fully dilute PDCs (also known as surges), but it is also possible in dense granular currents (e.g., Smith et al., 2020). The range of grain sizes evident in xspB and the evidence of abrasion of the smaller pumices indicate that the currents involved were not fully dilute or ash-rich (cf. Valentine and Giannetti, 1995). Minor fines-rich zones may have been generated by changes in supply to the flow-boundary zone or by variable influence of fallout material.

We propose that the hybrid xspB facies reported here formed during a short-lived phase where very proximal fallout interacted with turbulent density currents, in a setting similar to the "impact zone" envisaged by Valentine (2020).

## SIGNIFICANCE

This study provides a novel example of simultaneous primary volcanic deposition in the complex proximal domain, representing a previously unreported part of the spectrum of hybrid deposition.

Numerical modeling exploring proximal ignimbrite-forming processes has shown that an influx of coarse material into a collapsing column can translate into formation of dense flows in a proximal "impact zone," which are overridden by dilute currents of expelled fines (Valentine, 2020, and references therein). This modeling could explain the fines-poor nature of the xspB facies reported here. Greater recognition of hybrid processes in the rock record can

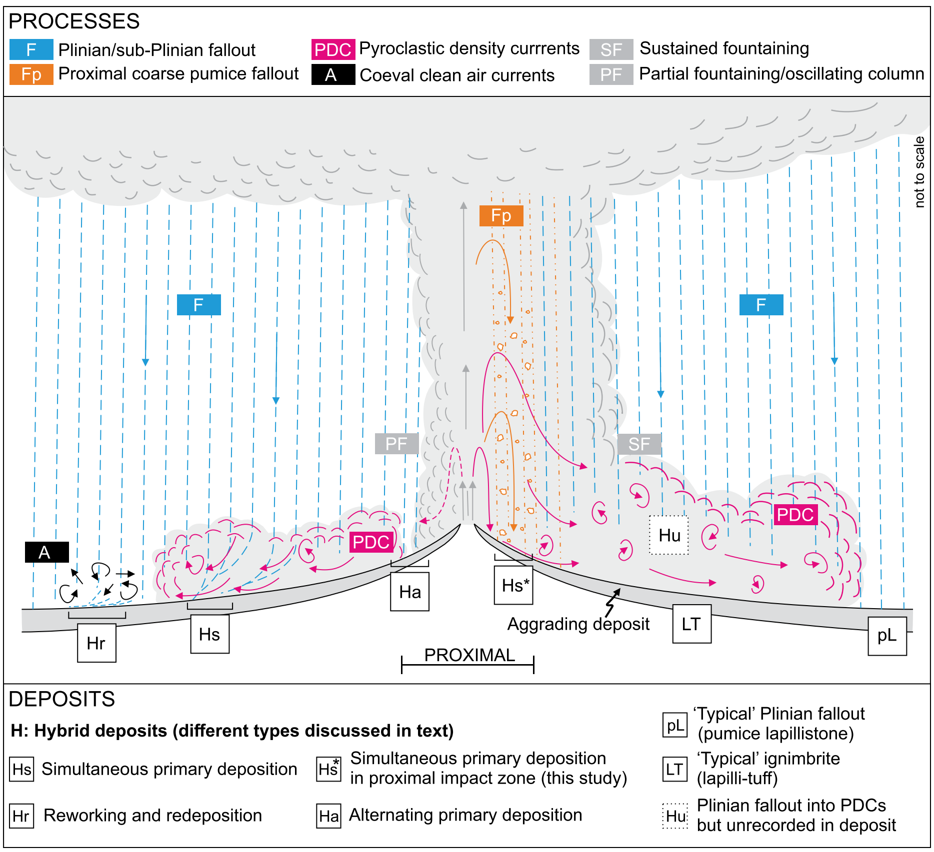


**Figure 4. Schematic of a Plinian eruption summarizing the styles of hybrid deposition discussed in the text. Colored boxes define processes, and white boxes are deposit types.**

inform future modeling, allowing us to more confidently understand how fallout and flow may interact and impact hazard assessments around a volcano.

It is important to recognize the "gray areas" in field volcanology. It is widely appreciated that complexities such as bypass and erosion are inherent aspects of PDC activity that can be cryptic in the rock record (e.g., Brown and Branney, 2004). Hybrid processes may be similarly cryptic. Hybrid facies created by reworking during hiatuses can only be preserved where not eroded by a subsequent PDC. Those recording Plinian fallout into a PDC are likely only recorded where currents wane sufficiently to allow fallout to dominate the deposit or where Plinian material is coarse/dominant enough to be recognized (this study).

We suggest that hybrid processes should be seen as inherent in Plinian eruptions and given greater consideration. Different hybrid processes are likely to occur both at different locations around the volcano and during different stages of an eruption. A snapshot of this complexity is illustrated in Figure 4. It follows that hybrid pyroclastic units may be more common than is reported. Where recorded, they can be difficult to distinguish from fallout or PDC deposits. An interpretation of ignimbrite may lead to the involvement of fallout being underestimated, while identification as fallout could lead to the existence of PDCs at a study location being overlooked. Whatever the location on the volcano, correct hazard identification is the ideal, but acknowledgment of the potential complexity and uncertainty highlighted by studies such as this one is perhaps just as important to hazard modeling and assessment.


## ACKNOWLEDGMENTS

We acknowledge Natural Environment Research Council studentships NE/G523855/1 and NER/S/A/2006/14156. We thank P. Rowley, D. Brown, G. Valentine, and C. Wilson for their reviews.


## REFERENCES CITED


Bonadonna, C., Connor, C.B., Houghton, B.F., Connor, L., Byrne, M., Laing, A., and Hincks, T.K., 2005, Probabilistic modeling of tephra dispersal: Hazard assessment of a multiphase rhyolitic eruption at Tarawera, New Zealand: Journal of Geophysical Research, v. 110, B03203, https://doi.org/10.1029/2003JB002896.

Branney, M.J., and Kokelaar, P., 2002, Pyroclastic Density Currents and the Sedimentation of Ignimbrites: Geological Society, London, Memoir 27, 143 p., https://doi.org/10.1144/gsl.mem.2003.027.

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

Brown, R.J., and 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, v. 75, 727, https://doi.org/10.1007/s00445-013-0727-0.

Bursik, M.I., and Woods, A.W., 1996, The dynamics and thermodynamics of large ash flows: Bulletin of Volcanology, v. 58, p. 175–193, https://doi.org/10.1007/s004450050134.

Cioni, R., Pistolesi, M., and Rosi, M., 2015, Plinian and subplinian eruptions, *in* Sigurdsson, H., ed., Encyclopedia of Volcanoes (2nd ed.): San Diego, California, Academic Press, p. 519–535, https://doi.org/10.1016/B978-0-12-385938-9.00029-8.

Cole, P.D., Guest, J.E., Duncan, A.M., and Pacheco, J.M., 2001, Capelinhos 1957–1958, Faial, Azores: Deposits formed by an emergent Surtseyan eruption: Bulletin of Volcanology, v. 63, p. 204–220, https://doi.org/10.1007/s004450100136.

Di Muro, A., Neri, A., and Rosi, M., 2004, Contemporaneous convective and collapsing eruptive dynamics: The transitional regime of explosive eruptions: Geophysical Research Letters, v. 31, L10607, https://doi.org/10.1029/2004GL019709.

Di Muro, A., Rosi, M., Aguilera, E., Barbieri, R., Massa, G., Mundula, F., and Pieri, F., 2008, Transport and sedimentation dynamics of transitional explosive eruption columns: The example of the 800 BP Quilotoa Plinian eruption (Ecuador): Journal of Volcanology and Geothermal Research, v. 174, p. 307–324, https://doi.org/10.1016/j.jvolgeores.2008.03.002.

Dowey, N.J., Kokelaar, B.P., and Brown, R.J., 2020, Counting currents: Correlating flow units to understand how pyroclastic density currents wax and wane in time and space: Poster presented at the Volcanic and Magmatic Studies Group Annual Conference, 7–9 January 2020: Plymouth, UK: Volcanic and Magmatic Studies Group https://vmsg.org.uk/wp-content/uploads/2020/01/Abstract_Volume_Plym2020.pdf.

Doyle, E.E., Hogg, A.J., Mader, H.M., and Sparks, R.S.J., 2010, A two-layer model for the evolution and propagation of dense and dilute regions of pyroclastic currents: Journal of Volcanology and Geothermal Research, v. 190, p. 365–378, https://doi.org/10.1016/j.jvolgeores.2009.12.004.

Druitt, T.H., and Sparks, R.S.J., 1982, A proximal ignimbrite breccia facies on Santorini, Greece: Journal of Volcanology and Geothermal Research, v. 13, p. 147–171, https://doi.org/10.1016/0377-0273(82)90025-7.

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

Fisher, R.V., and Schmincke, H.-U., 1984, Pyroclastic flow deposits, *in* Fisher, R.V., and Schmincke, H.-U., eds., Pyroclastic Rocks: Berlin, Springer, p. 186–230, https://doi.org/10.1007/978-3-642-74864-6_8.

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

Myers, M.L., Wallace, P.J., Wilson, C.J.N., Morter, B.K., and 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, v. 451, p. 285–297, https://doi.org/10.1016/j.epsl.2016.07.023.

Neri, A., and Dobran, F., 1994, Influence of eruption parameters on the thermofluid dynamics of collapsing volcanic columns: Journal of Geophysical Research: Solid Earth, v. 99, p. 11,833–11,857, https://doi.org/10.1029/94JB00471.

Pyle, D.M., 1989, The thickness, volume and grainsize of tephra fall deposits: Bulletin of Volcanology, v. 51, p. 1–15, https://doi.org/10.1007/BF01086757.

Smith, G., Rowley, P., Williams, R., Giordano, G., Trolese, M., Silleni, A., Parsons, D.R., and Capon, S., 2020, A bedform phase diagram for dense granular currents: Nature Communications, v. 11, 2873, https://doi.org/10.1038/s41467-020-16657-z.

Smith, N., 2012, Near-Vent Processes of the 273 ka Poris Eruption (Tenerife) [Ph.D. thesis]: Liverpool, UK, University of Liverpool, 300 p., https://livrepository.liverpool.ac.uk/6253/.

Smith, N.J., and Kokelaar, B.P., 2013, Proximal record of the 273 ka Poris caldera-forming eruption, Las Cañadas, Tenerife: Bulletin of Volcanology, v. 75, 768, https://doi.org/10.1007/s00445-013-0768-4.

Sulpizio, R., Dellino, P., Doronzo, D.M., and Sarocchi, D., 2014, Pyroclastic density currents: State of the art and perspectives: Journal of Volcanology and Geothermal Research, v. 283, p. 36–65, https://doi.org/10.1016/j.jvolgeores.2014.06.014.

Valentine, G.A., 2020, Initiation of dilute and concentrated pyroclastic currents from collapsing mixtures and origin of their proximal deposits: Bulletin of Volcanology, v. 82, 20, https://doi.org/10.1007/s00445-020-1366-x.

Valentine, G.A., and Giannetti, B., 1995, Single pyroclastic beds deposited by simultaneous fallout and surge processes: Roccamonfina volcano, Italy: Journal of Volcanology and Geothermal Research, v. 64, p. 129–137, https://doi.org/10.1016/0377-0273(94)00049-M.

Valentine, G.A., Palladino, D.M., DiemKaye, K., and Fletcher, C., 2019, Lithic-rich and lithic-poor ignimbrites and their basal deposits: Sovana and Sorano formations (Latera caldera, Italy): Bulletin of Volcanology, v. 81, 29, https://doi.org/10.1007/s00445-019-1288-7.

Walker, G.P.L., 1971, Grain-size characteristics of pyroclastic deposits: The Journal of Geology, v. 79, p. 696–714, https://doi.org/10.1086/627699.

Walker, G.P.L., Wilson, C.J.N., and Frogatt, P.C., 1980, Fines-depleted ignimbrite in New Zealand—The product of a turbulent pyroclastic flow: Geology, v. 8, p. 245–249, https://doi.org/10.1130/0091-7613(1980)8<245:FIINZT>2.0.CO;2.

Williams, R., 2010, Emplacement of Radial Pyroclastic Density Currents over Irregular Topography: The Chemically-Zoned, Low Aspect-Ratio Green Tuff Ignimbrite, Pantelleria, Italy [Ph.D. thesis]: Leicester, UK, University of Leicester, 232 p.

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

Wilson, C.J.N., and Hildreth, W., 1998, Hybrid fall deposits in the Bishop Tuff, California: A novel pyroclastic depositional mechanism: Geology, v. 26, p. 7–10, https://doi.org/10.1130/0091-7613(1998)026<0007:HFDITB>2.3.CO;2.

Wilson, C.J.N., and Houghton, B.F., 2000, Pyroclast transport and deposition, *in* Sigurdsson, H., et al., eds., Encyclopedia of Volcanoes: San Diego, California, Academic Press, p. 545–554.

Zanon, V., Pacheco, J., and Pimentel, A., 2009, Growth and evolution of an emergent tuff cone: Considerations from structural geology, geomorphology and facies analysis of São Roque volcano, São Miguel (Azores): Journal of Volcanology and Geothermal Research, v. 180, p. 277–291, https://doi.org/10.1016/j.jvolgeores.2008.09.018.


Printed in USA