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

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ABSTRACT

The deposits of Plinian and sub-Plinian 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 and Pantelleria. The coarse pumice block facies has an openwork texture and correlates with distal Plinian units, but is cross-stratified and relatively poorly sorted with an erosional base. The facies is proposed to record the simultaneous interaction of very proximal fallout with turbulent PDCs, and reveals a fuller spectrum of hybrid deposition than previously reported. This work highlights the importance of recognising hybrid deposition both in the rock record and hazard modelling.

INTRODUCTION

Analysis of pyroclastic stratigraphy can reveal the behaviour 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 refs 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) disentangle hybrid lithofacies using previously reported examples, (2) define a new proximal hybrid lithofacies based on evidence from the 273 ka Poris Formation of Tenerife and the 46 ka Green Tuff of Pantelleria, and (3) discuss its significance for interpretation and modelling of volcanic hazards.

HYBRID LITHOFACIES

Deposits classified here as hybrid exhibit characteristics of both Plinian fallout (typically clast-supported and landscape-mantling; e.g. Walker, 1971) and ignimbrite deposited by PDCs (typically ash and pumice-rich and 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 vent (e.g. Cioni et al., 2015).

Simultaneous primary deposition

Valentine & Giannetti (1995) describe a hybrid lithofacies generated by primary volcanic fallout and PDC processes operating simultaneously within the White Trachytic Tuff, 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 comprises 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 (see Valentine et al., 2019 for review). Modelling 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 refs therein). Di Muro et al. (2008) describe a hybrid lithofacies recording this transitional regime in the 800 BP Quilotoa succession, Ecuador. The A2 sub-member of Unit U1 comprises 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 bedforms occur and the facies grades laterally into a pumice lapilli bed.

Alternating facies in the 1912 Novarupta proximal succession, Alaska, are 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, is proposed to record fallout deposited during intervals between discrete PDC units from a plume that maintained buoyant and non-buoyant 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 ambient wind or water during a hiatus in the eruption (e.g. Yellowstone, Myers et al., 2016). The syn-eruptive 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 & Hildreth (1998) describe a hybrid fall deposit in the Bishop Tuff, California, distinguished by variable cross-bedding and the presence of sub-rounded pumice lapilli, interpreted to record redeposition of Plinian fallout by wind vortices driven by air currents into coeval PDCs.

A 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). Here we report a proximal hybrid lithofacies (referred to throughout as xspB) found at Las Cañadas Caldera, Tenerife and Pantelleria, Italy.

The 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). 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). 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 (σ_Φ 1.7, see Fig 1B for grainsize 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 sub-rounded, while large lapilli and blocks (20-300 mm) are sub-angular 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 1A), and occasional internal cross-stratification of pumice clasts (Fig. 2B). Three dimensional cuts show that xspB beds thin and thicken both laterally and longitudinally (Fig 1A). The xspB facies is in gradational to erosive contact with stratified lithic-rich lapilli-tuff below, and is overlain by stratified to massive lapilli-tuff with a locally erosive contact (Fig 1A). It is poorer in ash and lithic content (by 15% and 14% respectively at Fig. 1 locality) and better sorted than the massive lapilli-tuff. The xspB facies is distinct from bedded pumice lapilli at the base of the succession by the pumice blocks (Fig, 2A), poorer sorting (σ_Φ 1.7 versus σ_Φ 1.3; Fig 1B), cross-stratification and variable ash content (Fig. 1A).

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).

The 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 (σ_Φ 1.6, Fig 3B), cross-stratified pumice-block facies (xspB). The facies comprises angular pumice lapilli and blocks (<275 mm) and subordinate poly-lithic 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 (~20-30°), not unidirectional and transverse to inferred current direction. Locally, lithic-rich scours <300 mm thick and <500 mm wide, >40% lithics, occur at the base of xspB, with basal contacts cutting into the units below (Fig. 3A).

The xspB facies grades vertically from a massive pumice lapilli facies with a locally erosive contact, and is overlain by welded ignimbrite; xspB is distinct from the underlying unit in that it contains larger pumice and lithic blocks and exhibits poorer sorting (Fig. 3B), has a wider range of lithic clast compositions, and is cross-stratified. It correlates compositionally (Zr ppm) and stratigraphically with a pumice (or ash) fall layer in coastal sections (Williams et al., 2014).

Interpretation

The xspB facies differs from proximal lithic-rich breccias (e.g. Druitt and Sparks, 1982). It is dominated by pumice (with 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 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 that 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 sub-angular pumice blocks, areal continuity, (variable) openwork 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 grainsize to associated Plinian fallout (Figs 1B and 3B), and at Pantelleria displays higher-angle cross-stratification than the hybrid facies created by fallout into dilute PDCs described by Valentine and Gianetti (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. 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 grainsize 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 were deposited from a low-fountaining collar of fallout ejecta (as invoked by Fierstein et al., 1997) and smaller material was 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 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 exhibits cross-stratification. Cross-stratification indicates traction-dominated deposition and migration of bedforms at the flow boundary zone (sensu Branney and Kokelaar, 2002). This has typically been associated with fully-dilute PDCs (aka surges), but is also possible in dense granular currents (e.g. Smith et al., 2020). The range of grainsize evident in xspB, and evidence of abrasion of the smaller pumices, indicates 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 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 modelling 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 refs therein). This modelling could explain the fines-poor nature of the xspB facies reported here. Greater recognition of hybrid processes in the rock record can inform future modelling, allowing us to more confidently understand how fallout and flow may interact and impact hazard assessments around a volcano.

It is important to recognise the “grey 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 recognised (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 at different stages of an eruption. A snapshot of this complexity is illustrated in Fig. 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, whilst 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 perhaps just as important to hazard modelling and assessment is acknowledgement of the potential complexity and uncertainty highlighted by studies such as this.

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SUPPLEMENTARY DATA

Methods and imagery

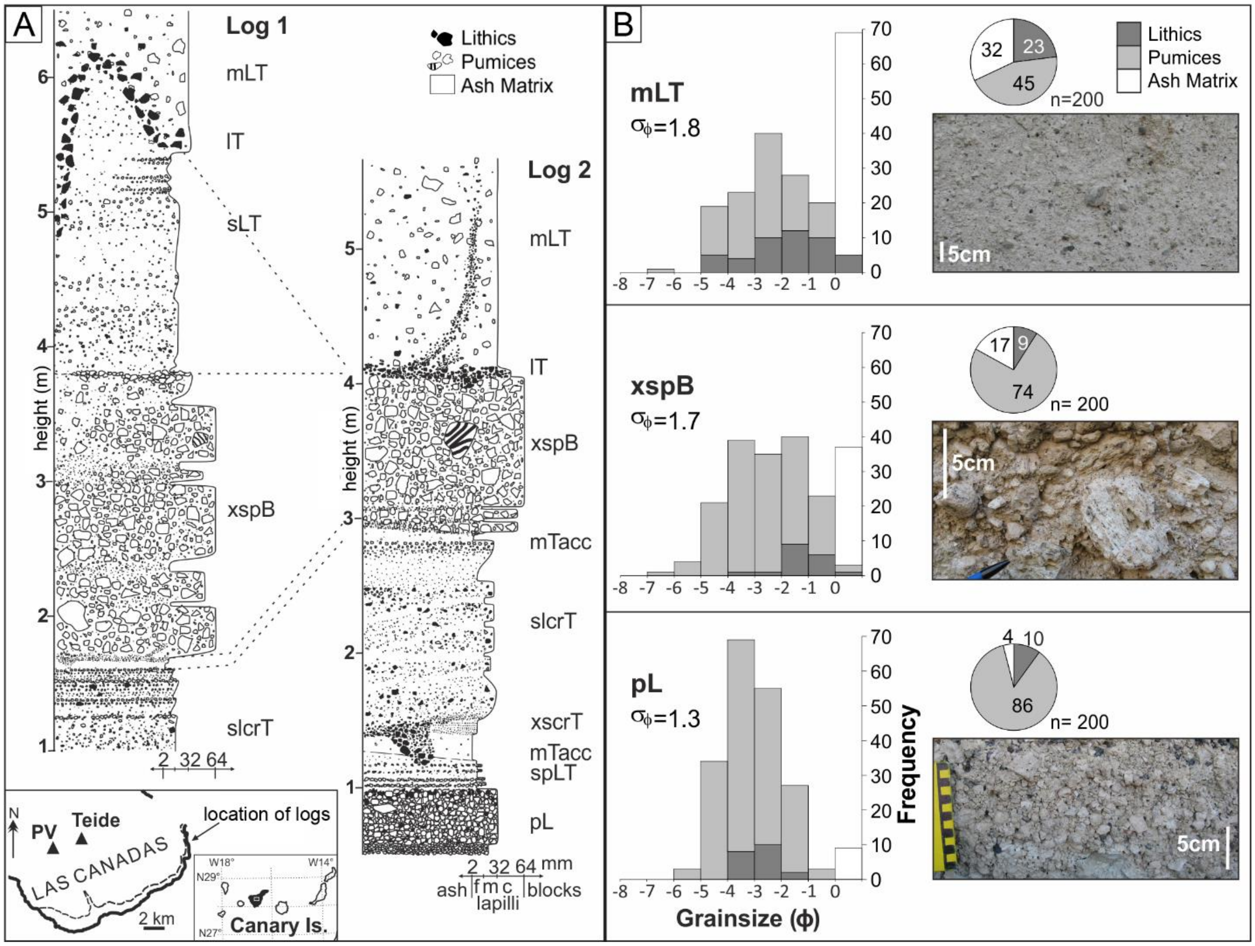

Figure 1: (A) The xspB facies at Las Cañadas (inset; stratigraphic logs 20 m apart at 28.280273, -16.549526). Facies abbreviation key shown in Figure 3. (B) Grainsize distribution histograms and pie charts illustrate comparative grainsize, sorting and componentry (see Supplement).

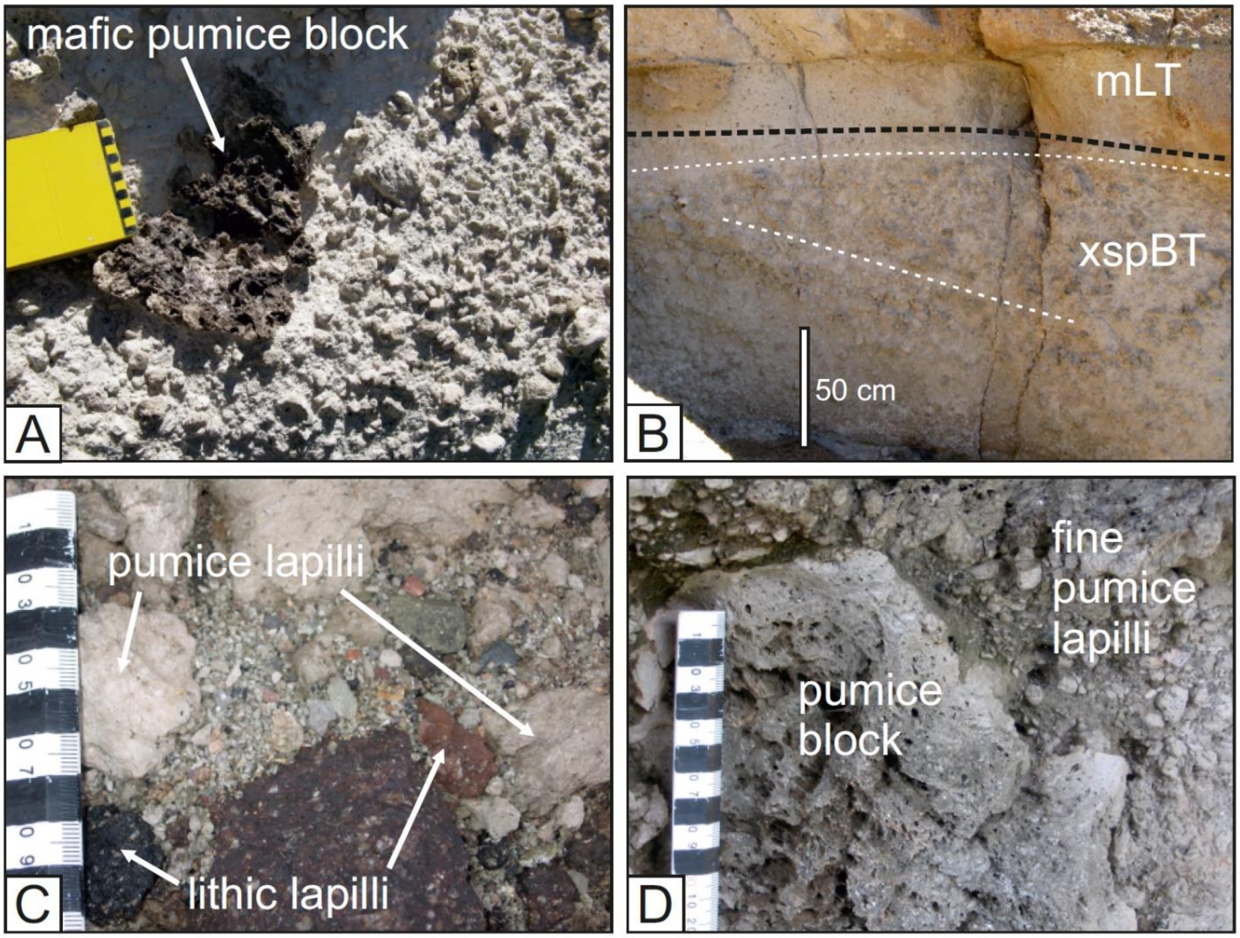

Figure 2: The xspB facies at Las Cañadas [(A) clast supported, with phonotephrite pumice block (28.270853, -16.545632); (B) exhibiting internal cross stratification (28.267141, -16.546145)] and at Bagno dell'Acqua (36.819358, 11.988439) [(C) poorly-sorted polylithic-rich lens; (D) coarse pumice blocks alongside more rounded pumice lapilli (scale in 10 mm)].

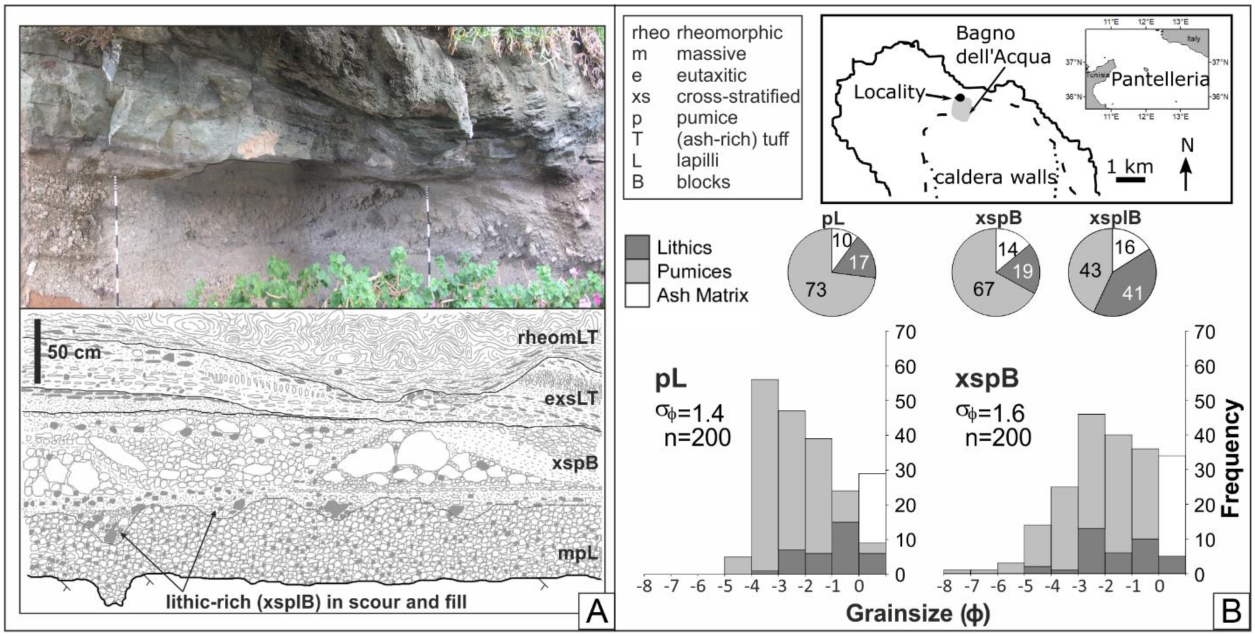

Figure 3: (A) Photo panel depicting xspB at Bagno dell'Acqua (inset; 36.819358, 11.988439), atop pumice lapillistone and overlain by eutaxitic, cross-stratified lapilli-tuff. (B) Grainsize distribution histograms and pie charts illustrate comparative grainsize, sorting and componentry (see Supplement).

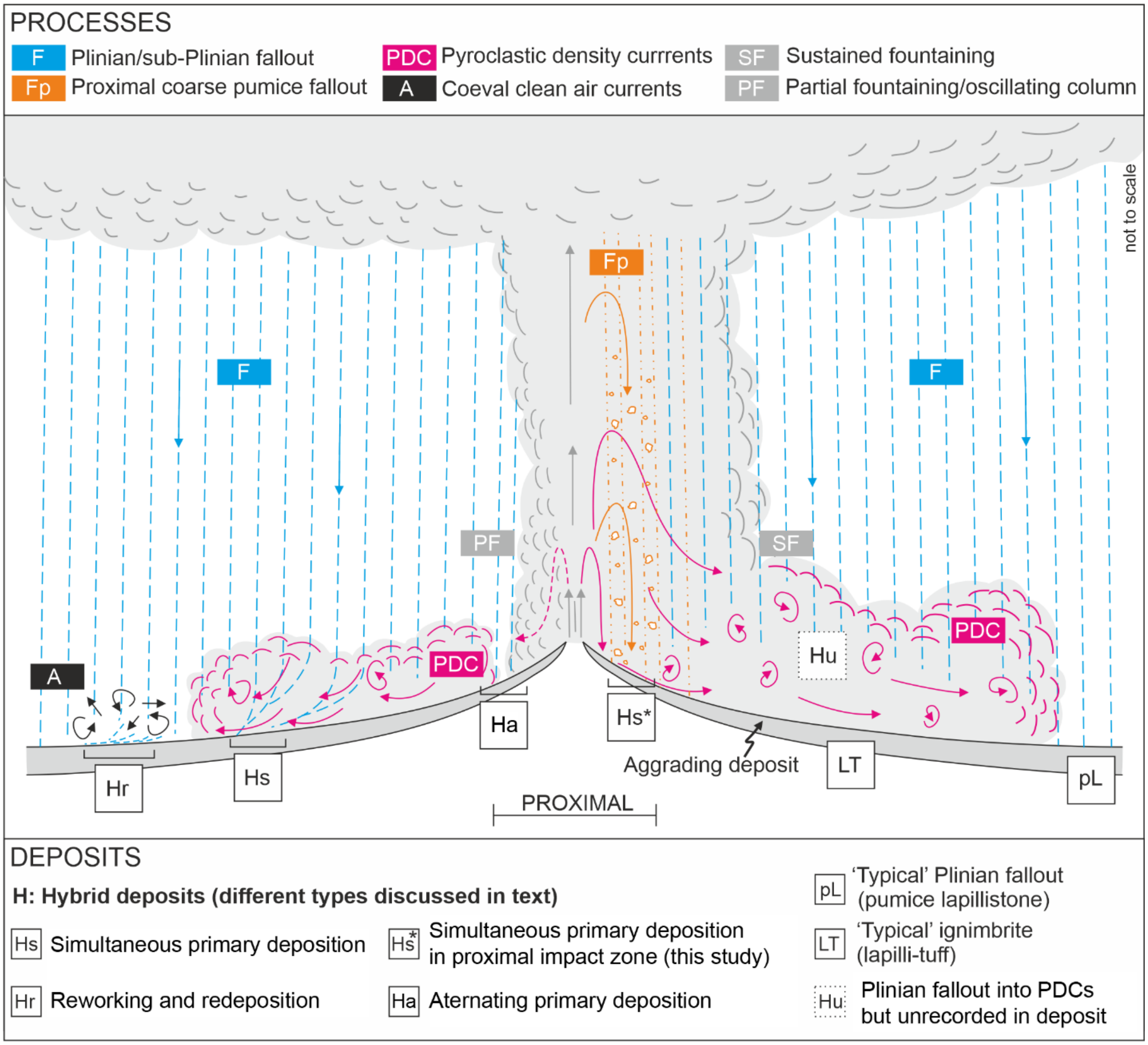

Figure 4: Schematic of a Plinian eruption summarising styles of hybrid deposition discussed in the text. Coloured boxes define processes and white boxes are deposit types.