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, UK, S1 1WB*

[2]*Department of Geography, Geology and Environment, University of Hull, UK, HU6 7RX*

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 flow perspective, with little attention given to facies exhibiting characteristics of both processes. Such hybrid deposits may be created where fallout and flow act simultaneously, where a transitional phase between perceived end members occurs, and/or due to reworking. This study presents new analysis of a novel facies on Tenerife and Pantelleria that records simultaneous proximal fallout and flow processes. The findings reveal a fuller spectrum of hybrid deposition than previously reported. Many hybrid lithofacies are likely misidentified or cryptic in the rock record; this work highlights the importance of recognising uncertainty in lithofacies interpretation, and of considering hybrid deposition in hazard modelling.

INTRODUCTION

Analysis of pyroclastic stratigraphy can reveal the behaviour and magnitude of explosive eruptions (e.g. Fisher, 1966), 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 are typically interpreted to record either plume (fallout) or pyroclastic density current (flow) 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 significance for interpretation and modelling of volcanic hazards.

HYBRID LITHOFACIES

Deposits classified here as 'hybrid' exhibit characteristics of both Plinian fallout (typically clast-supported, landscape-mantling; e.g. Walker, 1971) and ignimbrite deposited by PDCs (typically ash-rich and poorly sorted; e.g. Fisher and Schmincke, 1984). Hybrid facies can vary significantly 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 processes

Valentine & Giannetti (1995) describe a hybrid lithofacies generated by primary volcanic fallout and PDC processes operating simultaneously within the White Trachytic Tuff, Roccamonfina volcano, 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 the currents and dominated the deposition.

Transition from Plinian fallout to PDC activity

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). Previously, interbedded deposits at this interface were often interpreted as switches between fall and flow regime, but modelling has shown 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; the A2 sub-member of Unit U1 in the 800 BP Quilatoa succession 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. Similar transitional stratigraphy has been reported at Novarupta in Alaska, where the interbedding of PDC facies within fallout dominated by pumice blocks records proximal deposition from a plume intermittently affected by partial column collapse (Fall 2/PDC2 of Houghton et al., 2004).

Reworking and redeposition

Deposits that exhibit characteristics of both fallout and flow processes may be created by reworking. Fallout units can be reworked by ambient wind or water during hiatus in the eruption (e.g. Yellowstone, Myers et al., 2016), or post-eruption (e.g. Tenerife, Brown and Branney, 2004). The syn-eruptive involvement of wind may create a lack of clear distinction between the deposits of Plinian fallout and a fully-dilute PDC (Wilson and Houghton, 1999). Wilson & Hildreth (1998) describe a hybrid fall deposit in the Bishop Tuff 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

We report a proximal hybrid lithofacies found at Las Cañadas Caldera, Tenerife and Pantelleria, Italy. Investigations of proximal 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).

The Poris Formation, Tenerife

The pyroclastic succession of the 273 Ka Poris eruption is exposed at Las Cañadas less than 4 km from the likely vent location (Smith and Kokelaar, 2013). Proximal outcrops occur across the 1.9 km wide Diego Hernandez wall, and distal Poris exposures occur 15-20 km away in the coastal Bandas del Sur (e.g. Brown and Branney, 2004).

The proximal Poris succession includes a stratified to cross-stratified pumice-block facies (typically <2 m thick) consisting of pumice-rich beds 50-800 mm thick bounded by ash-rich beds <100 mm thick (Smith and Kokelaar, 2013). Three dimensional cuts show that pumice beds thin and thicken both across the wall and longitudinally (Fig 1A). 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 the facies is fully clast-supported (Fig. 2A).

Pumice blocks show no evidence of ballistic impact (such as sag structures or jigsaw-fit breakage). Pumices ≤20 mm in diameter are sub-rounded, while large lapilli and blocks (20-300 mm) are sub-angular to angular. Pumice beds display planar and low-angle cross-stratification (Fig 1A), and occasional internal cross-stratification of pumices (Fig. 2B).

The lithofacies is in gradational to erosive contact with stratified lithic-rich lapilli-tuff. It is overlain by stratified to massive lapilli-tuff with a locally erosive base (Fig 1A). It is poorer in ash and lithic content (by 15% and 14% respectively at Fig. 1 locality) and less poorly sorted than the massive lapilli-tuff. It is distinct from bedded pumice lapilli at the base of the succession by the pumice blocks (Fig, 2A), poorer sorting (σ_Φ 1.7 compared to σ_Φ 1.3; Fig 1B), cross-stratification and variable ash content (Fig. 1A).

In the distal Poris, two discrete clast-supported pumice lapilli facies record Plinian fallout (members 1 and 5 of Brown and Branney, 2013). The proximal facies described here 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, the proximal Green Tuff succession contains discontinuous horizons of a clast-supported, poorly-sorted (σ_Φ 1.6, Fig 3B), cross-stratified pumice-block facies. It comprises angular pumice lapilli and blocks (<275 mm) and subordinate poly-lithic lapilli and blocks (<77 mm) (Fig. 2). Lithic clasts vary in size, and are not systematically smaller than pumices (Fig 3B). Local lithic- and pumice-rich lenses occur and vary in sorting and componentry (Fig. 3).

Cross-stratification in the facies is at relatively high angle (~20-30°), not unidirectional and transverse to inferred current direction (Fig. 3). Locally, small lithic-rich lenses (<300 mm deep and <500 mm wide, >40% lithics) occur at the base of the hybrid facies, cutting into the units below (Fig. 3).

The lithofacies grades vertically from a massive pumice lapilli facies (Fig. 3); locally, this contact is erosive. It is distinct from this underlying facies 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 is overlain by welded ignimbrite. It correlates compositionally (Zr ppm) and stratigraphically with the pumice (or ash) fall layer in coastal sections (Williams et al., 2014).

Interpretation

The cross-stratified pumice-block lithofacies 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 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, it 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 the facies 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, the facies contains distinctly coarse and poorly sorted pumice blocks.

The cross-stratified pumice block lithofacies exhibits characteristics of both fall and flow. The sub-angular pumice blocks, areal continuity, (variable) openwork texture, and correlation with Plinian units are indicative of fallout (e.g. Walker, 1971). The cross-stratification, relatively poor sorting, erosional base, and lack of aerodynamic equivalence between adjacent clasts suggest PDC activity (e.g. Branney and Kokelaar, 2002).

The facies differs from previously reported hybrid facies. It has a different grainsize to associated Plinian fallout, 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 overlay Plinian fallout facies (Tenerife), nor does it contain interbedded strata (c.f. Di Muro et al., 2008). However, the dominance of pumice blocks is akin to the coarse proximal fallout layers in the transitional sequence at Novarupta (Houghton et al., 2004).

The facies is interpreted to record primary volcanism; the proximal location makes extensive alluvial or aqueous reworking unlikely as there is no catchment or upslope source. The componentry of the facies differs to underlying and coeval pumice fall deposits making clear-air reworking of that facies unlikely (c.f. Wilson and Hildreth, 1998).

At Tenerife and Pantelleria, the increase in grainsize in the cross-stratified pumice block facies records an influx of coarser material at the vent. This may be due to shallower fragmentation resulting from vent widening (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, larger 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 the cross-stratified pumice-block facies (recorded in underlying tuff deposits; Brown and Branney, 2004; Smith and Kokelaar, 2013), but was unsteady and marked by waning episodes that led to changes in runout distance. During deposition of the proximal hybrid facies (~4 km from likely vent), distal PDC hiatus allowed contemporaneous Plinian fallout to be recorded at the coast (Dowey et al., 2020). On Pantelleria, the facies 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); the facies is not longitudinally extensive and is absent at distal locations.

The 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 shown in recent work to also be possible in dense granular currents (Smith et al., 2020). The range of grainsize evident in the facies, and evidence of abrasion of the smaller pumices, indicates that the currents involved were not fully-dilute and ash-rich (c.f 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 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 bridges a gap between previous field studies of proximal ignimbrites (e.g. Druitt and Sparks, 1982), proximal fallout (e.g. Houghton et al., 2004), and hybrid deposits (e.g. Valentine and Giannetti, 1995). It 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 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.

The work is important in re-emphasizing 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 hiatus 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 end member 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 assessment is acknowledgement of the potential complexity and uncertainty highlighted by studies such as this.

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SUPPLEMENTARY DATA

Methods and raw data

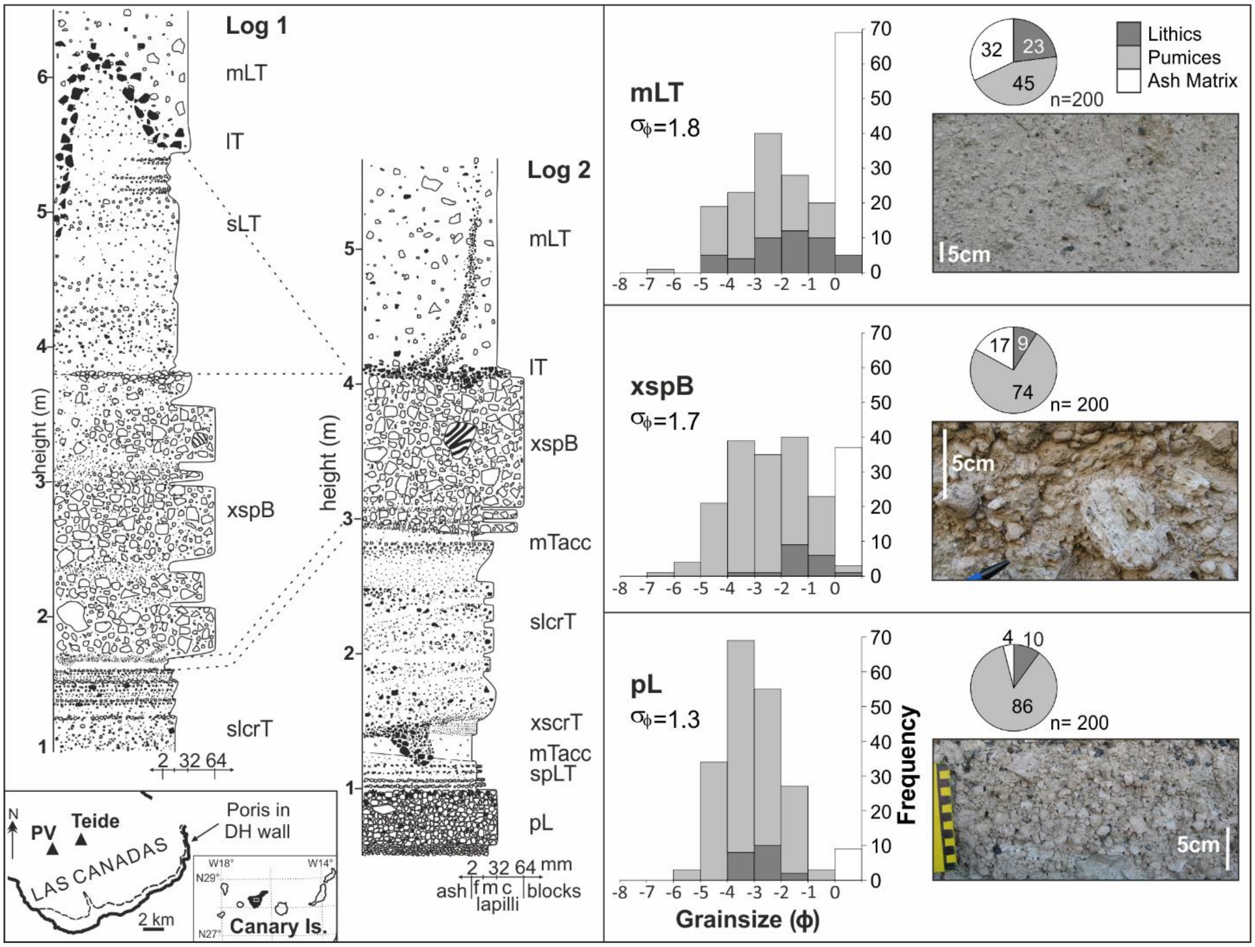

Figure 1: Poris cross-stratified pumice-block facies at Las Cañadas (inset; 28.280273, -16.549526; logs 20m apart). See Fig. 3 for facies key. Grainsize distribution histograms and pie charts illustrate comparative grainsize, sorting and componentry (see Methods Supplement).

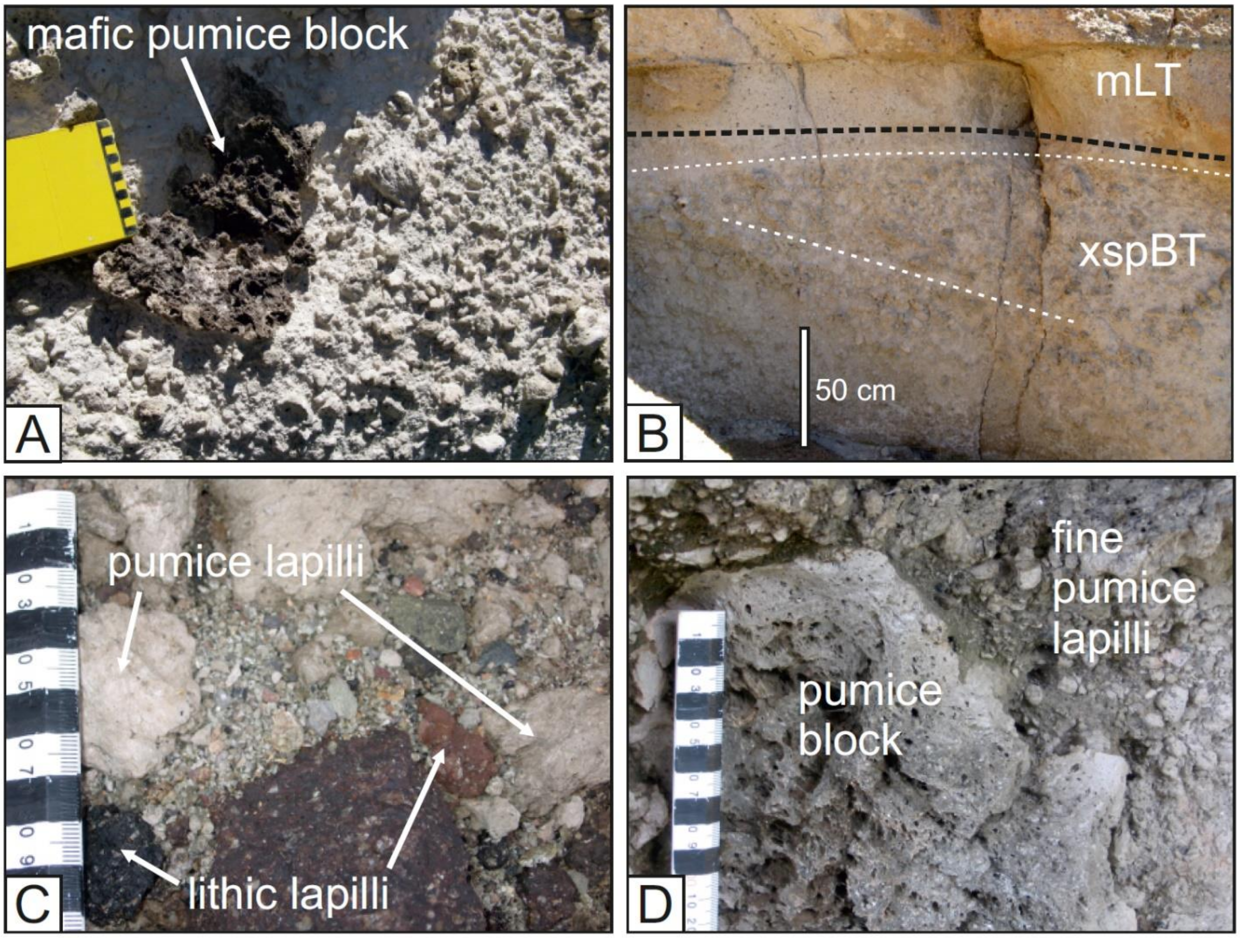

Figure 2: The hybrid facies at Las Cañadas [(A) clast supported, with phonotephrite pumice block (28.270853, -16.545632); (B) exhibiting internal cross stratification (28.267141, -16.546145)] and at Bagno dell'Acqua (36.819358, 11.988439) [(C) poorly-sorted polylithic-rich lens; (D) coarse pumice blocks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

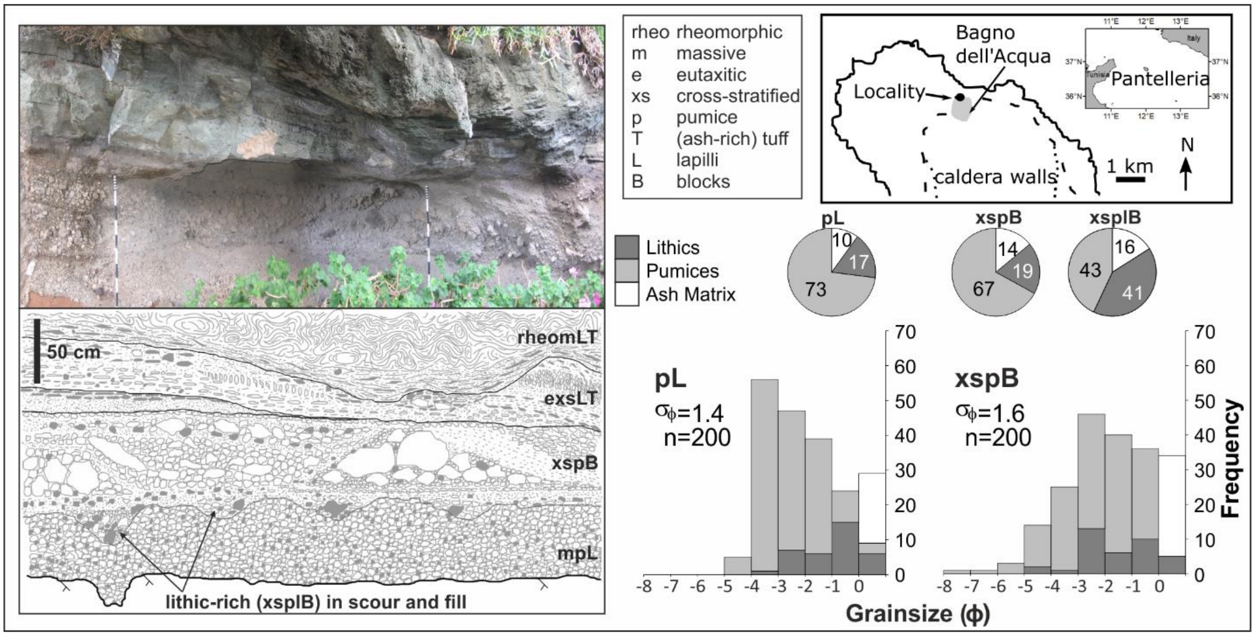

Figure 3: The hybrid facies at Bagno dell'Acqua (inset; 36.819358, 11.988439), atop pumice lapillistone and overlain by eutaxitic, cross-stratified lapilli-tuff.

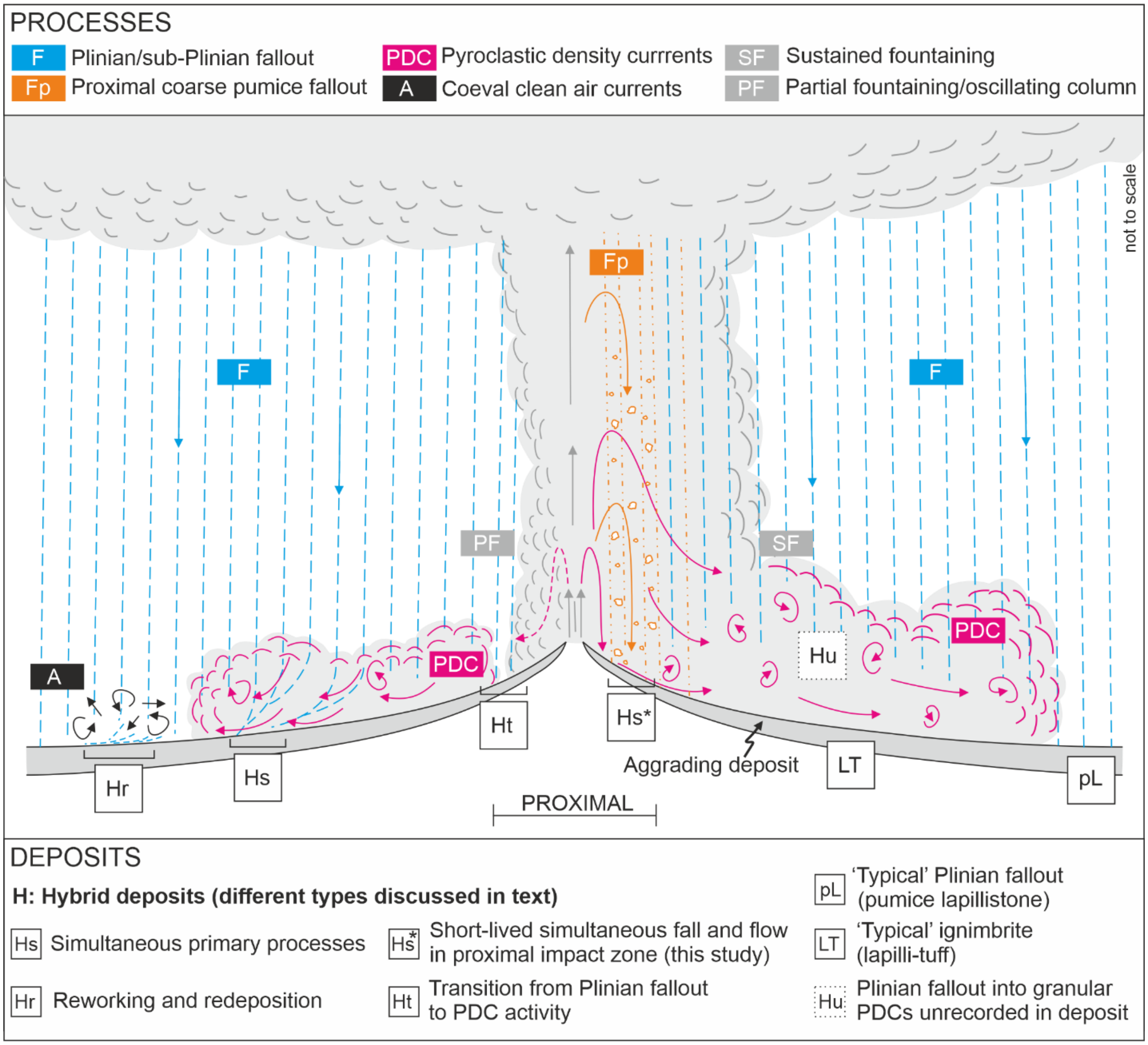

Figure 4: Schematic of a Plinian volcanic eruption summarising domains of hybrid deposition referenced in text. Processes are defined in coloured boxes and deposits are defined in white boxes.