New understanding of hybrid pyroclastic processes revealed from proximal deposits: implications for uncertainty in volcanic hazard assessment

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ABSTRACT

The deposits of Plinian and sub-Plinian eruptions provide critical insights into the behaviour and magnitude of past volcanic events, and inform numerical models that aim to mitigate against future volcanic hazards. However, pyroclastic deposits are often considered from either a fallout or flow perspective, with relatively little attention given to the complex spectrum of hybrid processes that occur between the two end members. This study provides new analysis of hybrid deposits generated by a combination of fallout from a Plinian/sub-Plinian plume and pyroclastic density current (flow) activity. We review previously reported hybrid lithofacies, present a novel lithofacies found on Tenerife and Pantelleria, and bring together a synthesis of hybrid processes as we currently understand them. The lithofacies reported here is a cross stratified pumice block tuff that records interaction between coarse fallout and pyroclastic density currents proximal (<5km) to the vent. Many hybrid lithofacies are likely misidentified or are cryptic in the rock record; improved consideration of these complex processes both in the field and in modelling will improve our understanding of the uncertainties inherent in the analysis of pyroclastic successions, therefore improving our analysis of eruption characteristics and volcanic hazards.

INTRODUCTION

Analysis of pyroclastic stratigraphy reveals critical insights into the behaviour of explosive eruptions (e.g. Fisher, 1966; Branney and Kokelaar, 2002), 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, 2005). However, the rock record is rarely complete, particularly in the zone closest to (<5 km) the vent, and investigations of proximal stratigraphy are rare (e.g. Druitt and Sparks, 1982; Rowley et al., 1985; Nairn et al., 2001; Houghton et al., 2004). In the proximal zone, multiple processes related to the eruption column, low fountaining and pyroclastic density current (PDC) activity are likely to impact the same geographic position at the same time. Deposits that capture these hybrid processes are common at tuff cones and maars (e.g. Cole et al., 2001; Zanon et al., 2009 and references therein), but there have been relatively few studies of hybrid deposits formed during Plinian eruptions (Valentine and Giannetti, 1995; Wilson and Hildreth, 1998; Di Muro et al., 2008). The lack of detailed study is likely because hybrid deposits are ambiguous or cryptic in the rock record and could be misinterpreted as either fallout or ignimbrite, with implications for interpretation of eruption dynamics and hazard analysis.

This study presents analysis of hybrid deposits that display evidence of deposition by a mixture of both Plinian fallout and PDC processes. We (1) briefly review previously reported hybrid lithofacies, (2) define a new type of proximal hybrid lithofacies based on evidence from the 273 ka Poris Formation of Tenerife and the 46 Ka Green Tuff of Pantelleria, and (3) present a synthesis of how these findings inform understanding and uncertainty in hazard dynamics.

PREVIOUS STUDIES OF HYBRID DEPOSITS

There have been only a handful of studies that have recognised and interpreted hybrid deposits in pyroclastic sequences (Supplementary Table 1). Here we use 'hybrid' to refer to lithofacies that exhibit characteristics of multiple processes, rather than interbedded deposits reflecting rapid changes in the dominant process. See Supplementary Table 2 for lithofacies code glossary.

Modification of fallout by PDC associated wind

Wilson & Hildreth (1998) described a hybrid fall deposit in the Bishop Tuff within a sequence of fall units that comprises moderately-sorted, angular pumice lapilli with parallel lamination and bedding. The hybrid lithofacies is differentiated by low-angle cross-lamination defined by coarser and finer pumice layers, and the presence of sub-rounded pumice lapilli (xspL). There is no evidence of scouring and the lithofacies is not persistent. There is no grain-size difference between the hybrid lithofacies and the enclosing fall lithofacies. Stratigraphically, the hybrid lithofacies correlates with PDC deposits nearby, but does not share characteristics with the Bishop Tuff ignimbrite; it is interpreted to record redeposition of tephra fallout by strong surface winds (clean air) associated with vortices from the PDCs.

Modification of ash fall deposits by wind associated with PDC activity has also been proposed in the Abrigo Ignimbrite, Tenerife (Pittari et al., 2006) and the Kos Plateau Tuff, Greece (Allen et al., 1999). These hybrid ash lithofacies are differentiated from ash fallout deposits by occasional low-angle cross-lamination and thickening or 'pinch and swell' of laminations.

Plinian fallout into PDCs

Valentine & Giannetti (1995) described a hybrid ignimbrite lithofacies (subunit E_1) within the White Trachytic Tuff, Roccamonfina volcano, Italy. At localities that contain the hybrid lithofacies, the ignimbrite is predominantly fine-grained ash, with minor pumice lapilli (LT). By contrast, the hybrid ignimbrite lithofacies is clast-supported and comprises angular pumices, ranging from coarse lapilli to small blocks (pL). The pumice layers grade from the ignimbrite, thicken and thin, and pinch out laterally within the ignimbrite lithofacies. The hybrid lithofacies is interpreted to record pumice fallout from an eruption column 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

DiMuro et al. (2008) describe a hybrid lithofacies thought to capture a “transitional regime” (Di Muro et al., 2004) in transport and depositional processes that occurs as an eruption column collapses. The A2 sub-member of Unit U1 in the 800 BP Quilatoa eruption sequence comprises alternating clast-supported pumice lapilli (pL) layers and beds of stratified ash, pumice- and lithic-lapilli (sT-sLT). Proximally, the sub-member is cross-stratified, whereas more distally, regressive and progressive bedforms occur (xsLT). The underlying clast-supported A1 sub-member records fallout from a convecting eruption column. The A2 sub-member is interpreted to record partial collapses of a transitional eruption column.

Similar units of laterally discontinuous, cross-stratified tuff interspersed with thin beds of pumice lapilli are recorded in the Faby Formation, Zaragoza Member, and the Rosa Formation at Los Humeros, Mexico (Willcox, 2012). They typically occur between clast-supported, well sorted pumice fall deposits (lapilli <20 mm) and deposits containing progressively more rounded pumice lapilli and increasing proportions of matrix (i.e. ignimbrite). They are interpreted to record the first pulses of PDC activity as the eruption transitioned from a pumice fall dominated regime to an ignimbrite-forming regime (Willcox, 2012).

A NEW TYPE OF PROXIMAL HYBRID LITHOFACIES

A new type of hybrid lithofacies has been recognised in proximal pyroclastic exposures at the Diego Hernandez wall of Las Canadas Caldera, Tenerife and on the island of Pantelleria, Italy. The facies comprises cross stratified to stratified pumice blocks and varies from clast supported to matrix supported (xspB(T)).

The Poris Formation, Tenerife

The pyroclastic succession of the 273 Ka Poris eruption (Brown et al., 2003) is exposed in the Las Cañadas caldera on Tenerife less than 4 km from the likely location of the vent (Smith and Kokelaar, 2013). Proximal outcrops are spread across the 1.9 km wide Diego Hernandez wall. Distal exposures are found across the coastal Bandas del Sur region (e.g. Brown and Branney, 2013), 15-20 km from proximal exposures.

The Poris proximal hybrid lithofacies is typically <2 m thick (Smith and Kokelaar, 2013). It is a stratified to cross stratified pumice block tuff (xspBT) that consists of pumice-rich beds 50-800 mm thick defined by bounding ash-rich beds <100 mm thick (Fig. 1). Three dimensional exposures show that pumice beds thin and thicken both across the wall and longitudinally. Pumice beds are poorly sorted and rich in pumice lapilli and blocks (5-300 mm), with rare lithic lapilli. The facies contains ~70-80% pumice clasts, and at one location is fully clast-supported (Fig. 2A). Pumice blocks show no evidence of ballistic impact. Pumices ≤20 mm in diameter are slightly rounded, while large lapilli and blocks (20-300 mm) are sub-angular to angular. The pumice beds display planar and low angle cross stratification, and occasionally internal cross stratification of pumices (Fig. 2B).

The xspBT lithofacies is in gradational to erosive contact, both above and below, with stratified to massive lapilli tuff lithofacies (s-mLT) that record PDC deposition. It is distinct from the well sorted, bedded pumice lapilli (bpL) facies at the base of the proximal succession that records deposition from a Plinian column (Smith and Kokelaar, 2013) by its coarser grainsize, poor sorting and cross stratification (Fig. 1; B and C).

In the distal Poris succession, two discrete clast-supported pumice lapilli facies record Plinian fallout (members 1 and 5 of Brown and Branney, 2013). The xspBT facies stratigraphically correlates with the upper distal fallout unit (Smith, 2012; Dowey et al., 2020).

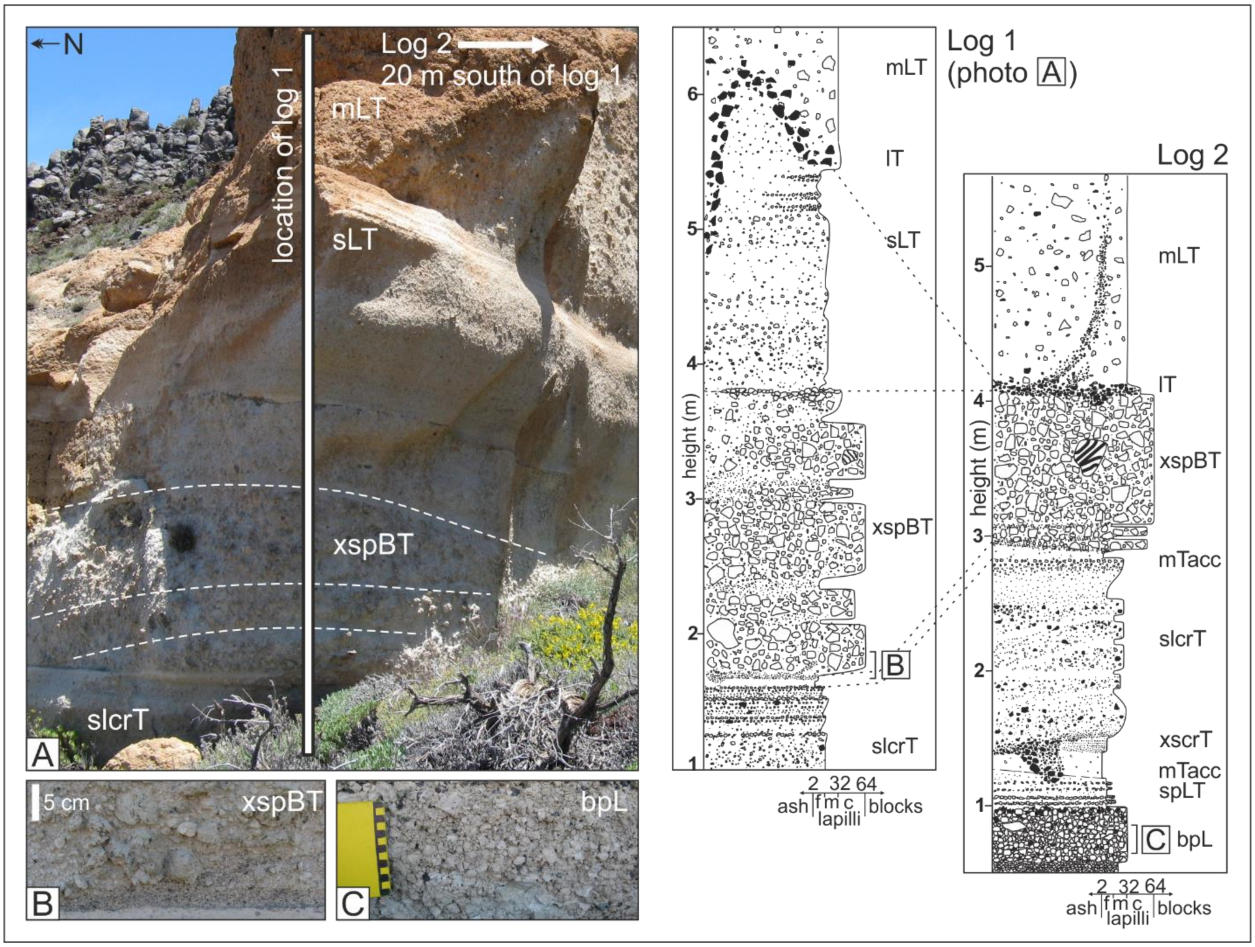

Figure 1: Graphic logs of the Poris Formation at the Digeo Hernandez wall, Tenerife (28.280273, -16.549526). Log 1 corresponds to photo (A). At this location, pumice-rich beds within xspBT exhibit low angle cross stratification. At log 2, a pumice lapillistone facies (bpL) at the base of the succession records Plinian fallout; bpL pumices are smaller, better sorted and more angular (B) than those in xspBT (C).

The Green Tuff Formation, Pantelleria

The 46 ka Green Tuff eruption (Williams et al., 2014) is well exposed across the island, from sections around the Cinque Denti caldera walls (<3 km of the vent) to coastal sections (<7 km from the vent). The Green Tuff Formation broadly comprises a pumice fall unit at its base and then a variably welded, rheomorphic ignimbrite (Williams, 2010; Williams et al., 2014). The Green Tuff proximal hybrid lithofacies is exposed in the Cinque Denti caldera wall at Bagno dell Acqua. It is a predominantly clast-supported, cross-stratified pumice-block (xspB(T)) facies that comprises angular pumice lapilli and blocks (<275 mm) and subordinate poly-lithic lapilli and blocks (77 mm) with local lenses of lithic-rich and pumice-blocks (Fig. 2; C and D). Lenses vary from poorly to very well sorted, though none are matrix-supported.

Cross-stratification in the facies is at relatively high angle (~20-30°), not unidirectional and transverse to the inferred current direction (Fig. 3). Dune-form bedding or other aggradational bedforms are not observed. Scour and fill structures filled with very poorly sorted, lithic rich lenses occur. These structures are small (<300 mm deep and <500 mm wide) and occur at the base of xspB(T), cutting into the facies below.

The xspB(T) facies grades vertically from a massive pumice-lapilli (mPL) facies (Fig. 3), interpreted to represent pumice fall from a sub-Plinian to Plinian column. Locally it has an erosive contact with the underlying mpL. It is distinct from mpL in that it contains larger pumice and lithic blocks (<113 mm pumice and 31 mm lithics in mpL), is less well sorted, has a wider range of lithic clast compositions and is cross-stratified. Above it lies the Green Tuff ignimbrite. Stratigraphically, it correlates with the pumice fall layer (or ash fall layer) in distal sections.

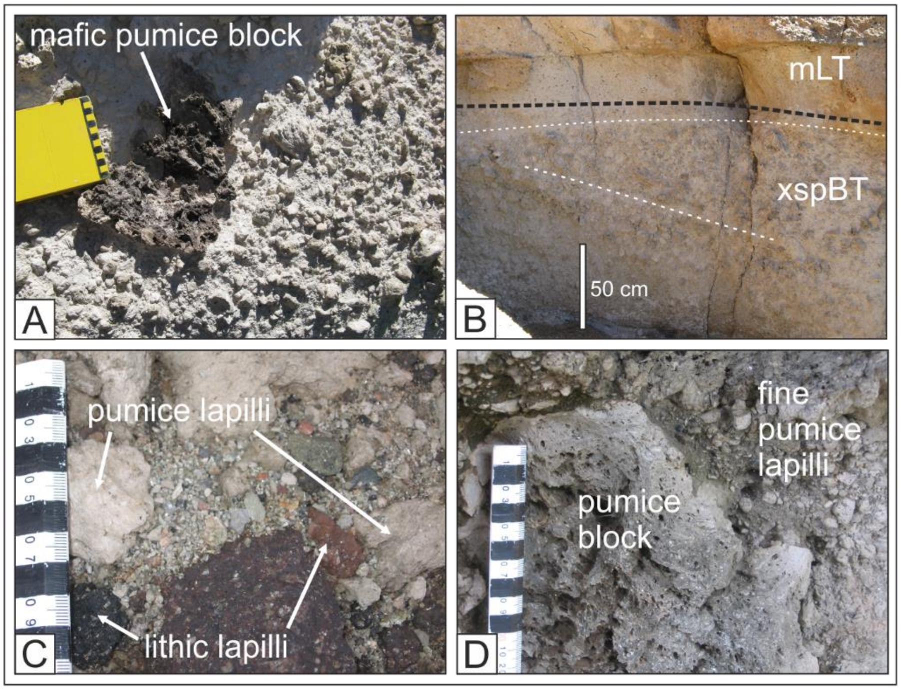

Figure 2: Hybrid proximal lithofacies at Tenerife and Pantelleria. The xspBT facies at the Diego Hernandez wall at Tenerife; (A) clast supported but poorly sorted, containing large mafic (phonotephrite) pumice blocks (28.270853, -16.545632), and (B) exhibiting internal cross stratification (28.267141, -16.546145). The Pantelleria xspB(T) facies at Bagno dell'Acqua (36.819358, 11.988439), showing (C) poorly-sorted polylithic-rich lens in scour and fill and (D) coarse pumice blocks alongside finer, more rounded pumice lapilli (scale divisions in 10 mm).

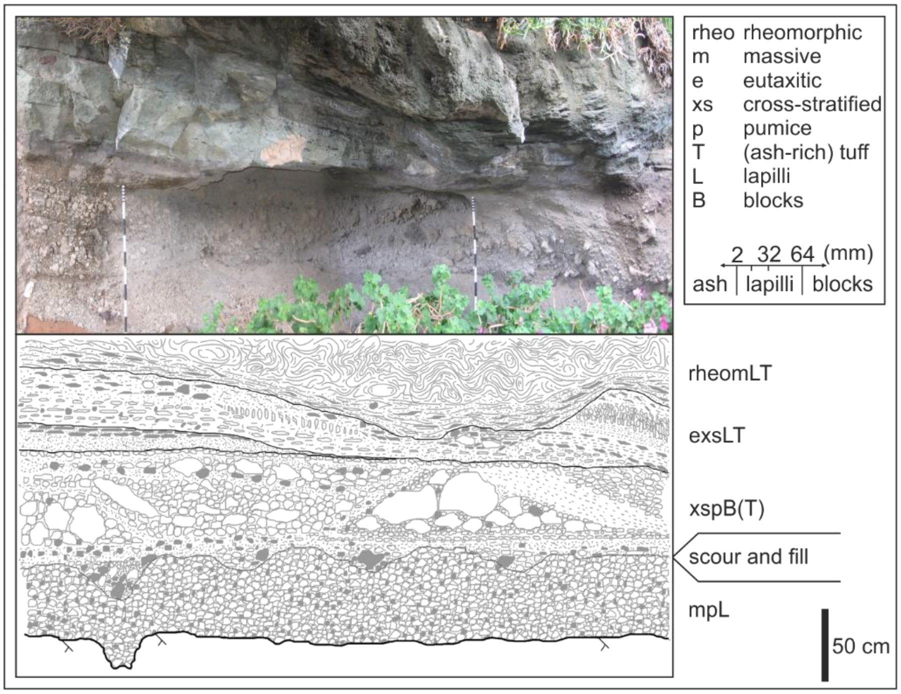

Figure 3: Photo and sketch of the Pantelleria massive pumice-lapilli facies (mpL) and the cross-stratified pumice block tuff facies (xspB to xspB(T)) with lithic rich lenses at Bagno dell'Acqua (36.819358, 11.988439). It is here overlain by eutaxitic, cross-stratified lapilli-tuff that grades vertically into rheomorphic massive lapilli-tuff (2 m thick, top not shown).

Interpretation

The xspB(T) lithofacies on Tenerife and Pantelleria exhibit characteristics distinct from typical ignimbrite lithofacies (described in Branney and Kokelaar, 2002); notably by the angularity of pumice clasts and the clast-supported, often openwork texture of the facies. These characteristics are more consistent with pumice fall deposits. However, the cross-stratification, poor sorting, erosional bases and scours, and lack of aerodynamic equivalence between adjacent clasts (i.e. lithic lapilli not systematically smaller than pumice lapilli) indicate that the lithofacies could not have been formed by fallout processes alone.

The proximal hybrid lithofacies (xspB/T) described here differs from previously described hybrid lithofacies; it has a different componentry to associated fall deposits, contains predominantly block-sized pumice clasts and large lithics, and displays higher-angle cross-stratification. Pumice clasts are angular to occasionally subrounded, and there are scour and fill structures. This facies cannot be a wind-modified fall deposit (c.f. Wilson and Hildreth, 1998), nor can it record fallout into dilute PDCs (c.f. Valentine and Giannetti, 1995). The lithofacies does not consist of interbedding of pumice-lapilli and lapilli-tuff, and is therefore not similar to the transition units of Di Muro (2008). Furthermore, the proximal caldera rim location of the cross-stratified pumice-lapilli facies described here is an unlikely location for extensive syn-eruption alluvial or aqueous reworking, as there is no catchment or upslope source; so we cannot interpret the facies as reworked material.

We interpret this lithofacies to record hybrid interaction between coarse proximal fallout from low-fountaining parts of a sub-Plinian to Plinian eruption column and granular PDCs that added a vigorous, lateral component. Coarse, poorly sorted proximal fallout material has previously been described in deposits of the 1912 Novarupta eruption in Alaska (Bed 'S' of Fierstein et al., 1997; Houghton et al., 2004b). The cross stratification in the lithofacies described in this study clearly distinguishes it as a proximal hybrid.

A NEW SYNTHESIS OF HYBRID PYROCLASTIC PROCESSES

Hybrid pyroclastic processes are likely ubiquitous in dynamic Plinian/sub-Plinian eruptions. However, to date, hybrid processes have not been widely recognised in the field and have not benefited from detailed summary. 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.

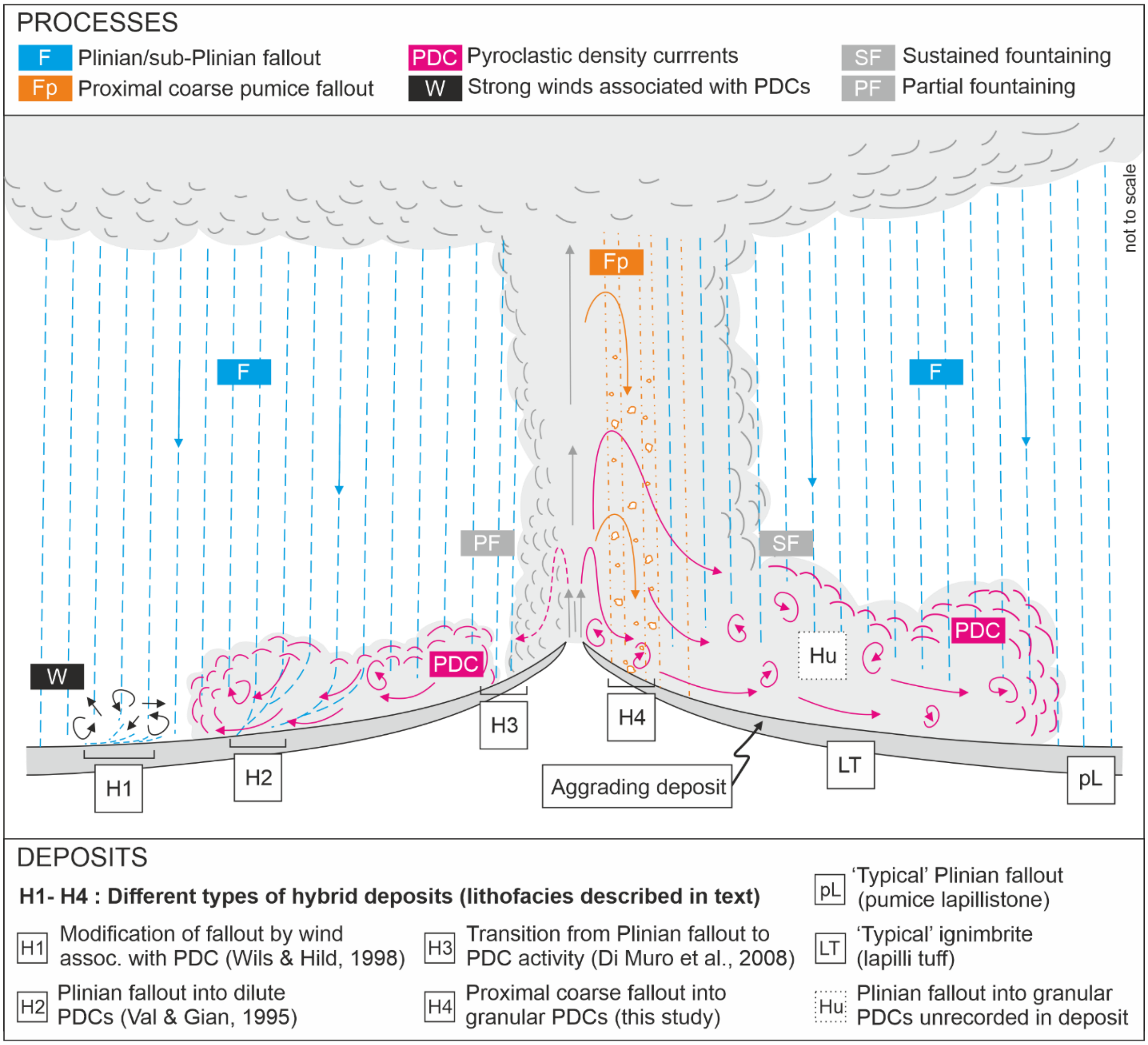

Figure 4: Schematic of a Plinian/sub-Plinian volcanic eruption illustrating domains of hybrid deposition. Processes are defined in coloured boxes and deposits are defined in white boxes (see legends).

Hybrid pyroclastic units may be more common than is reported in the literature, as they may be difficult to identify and distinguish from end member fallout or PDC deposits. The cross-stratification means they may be interpreted as an ignimbrite lithofacies, which may lead to an underestimation of the volume of tephra deposits from a plume. This could be particularly problematic when isopach mapping is used to calculate eruption size (e.g. Pyle, 1989; Bonadonna and Costa, 2012), or as an input parameter to computer modelling (e.g. de' Michieli Vitturi et al., 2016). Alternatively, they may be mistakenly identified as reworked pumice fall and the existence of PDCs in an eruption completely overlooked, significantly impacting estimates of eruption magnitude and hazard analysis.

Many hybrid processes may not be recorded in the rock record. Hybrid deposits created by winds associated with PDCs (H1, Wilson and Hildreth, 1998) would perhaps only be preserved where not immediately overrun or eroded by the PDC. Hybrid deposits recording Plinian fallout into a PDC are likely to only be recorded in the specific conditions described by Valentine and Giannetti (1995), where dilute currents wane sufficiently to allow fallout to dominate the resultant deposit (H2). Typical Plinian fallout into granular PDCs would be incorporated into the current and deposited along with other pumices in the ignimbrite (Hu), unrecognisable from the deposits of a PDC that had no contemporaneous Plinian fallout. Such fallout would only be recorded in the deposit during a temporary cessation of current activity at a given location (observed in the distal Poris Formation; Brown and Branney, 2013).

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). We propose that hybrid processes should also be seen as inherent in Plinian eruptions and given greater consideration.

Pyroclastic deposits remain one of the largest sources of information on eruption source parameters (Bonadonna et al., 2015). However, too often we consider them singularly from either a fallout or flow research perspective, rather than as the complex spectrum this study demonstrates them to be. Improved recognition of hybrid deposits and consideration of complex proximal scenarios when characterising past eruptions is essential to bridge the gap between disciplines, and to improve our understanding of potential uncertainties in numerical models and hazard analysis.

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SUPPLEMENTARY DATA

Table 1: Table comparing nature of the different reported hybrid deposits

Table 2: Glossary of PDC lithofacies abbreviations used