



A Confidence-Based Assessment Method for Distinguishing Pyroclastic Density Current Deposits From Other Volcaniclastic Units

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Pyroclastic density currents (PDCs) are a destructive volcanic hazard. Quantifying the types, frequency and magnitudes of PDC events is essential for effective risk management, but since historical records at best extend a few hundred years this usually relies on identifying deposits in the geological record. However, small volume unconsolidated PDC deposits have low preservation potential and can be difficult to distinguish from other volcaniclastic units, especially in proximal locations. Consequently many small or poorly exposed deposits can be overlooked. Here, we introduce a structured field method for assessing volcaniclastic deposits of unknown origin with a particular focus on identifying deposits from concentrated PDCs (pyroclastic flows). The method differs from traditional identification schemes in that it does not uniquely attribute a deposit to a single depositional process, but instead assesses how confidently different volcaniclastic processes could explain the observed deposit features. Therefore, the underlying uncertainties in the assessment are explicitly addressed. The method allows consistent, rapid assessment of candidate pyroclastic flow deposits in the field, and the concept could easily be adapted for assessing other types of volcaniclastic deposit. The introduction of confidence levels in deposit interpretations should be useful for carrying though uncertainties into probabilistic assessments of volcanic hazards.

Keywords: pyroclastic density current, pyroclastic flow, volcaniclastic, deposit, identification, classification, assessment

1 INTRODUCTION

A fundamental principle in volcanology is that a volcano's past behavior provides insight into the kind of activity that can be expected in the future. Therefore, quantifying the distributions, types, frequencies and magnitudes of previous hazards is an important component of volcanic hazard management (Nakada, 2000; Leonard et al., 2014). Since historical records only date back at most a few hundred years, this normally relies on identifying deposits in the geological record. However, it can be difficult to identify formative processes from small or poorly preserved deposits that lack distinguishing features, and absence of evidence is not always evidence of absence (White and Valentine, 2016). Therefore, properly assessing even small or poorly preserved deposits, and acknowledging any interpretative uncertainty, is essential for thoroughly understanding a volcano's past activity.

Volcanic cones are constructed by eruption of lavas and explosively erupted material from one or more vents. During and between eruptive episodes, non-volcanic erosion and transport processes rework these materials downslope to form a wide variety of fragmental deposits composed almost entirely of volcanic material. Thus, most volcanic surfaces present a diverse mix of primary and non-primary fragmental deposits (“volcaniclastic deposits;” e.g., McPhie et al., 1993) that can be difficult to distinguish in the field. In the case of historical deposits, identification is usually straightforward since the causative process is either observed directly, or significant amounts of the deposit remain (e.g., Cronin et al., 2013). Hence, modern deposits are well suited to traditional field assessment methods that emphasize broad initial observations of deposit geometry, followed by closer observations of outcrop-scale textures and components (Lube et al., 2007; Charbonnier et al., 2013). In contrast, because fragmental deposits are easily reworked on steep proximal volcanic slopes, many small or ancient deposits are commonly only preserved in a few poorly-exposed locations (e.g., Donoghue et al., 1999; Le Pennec et al., 2016). It is therefore more difficult to confidently assess small and ancient deposits in the absence of the broader-scale context that aids interpretation.

The motivation for this study was the observation of numerous unidentified volcaniclastic deposits at Mount Ruapehu (Cowlyn, 2016), an active andesitic-dacitic stratovolcano at the southern end of New Zealand’s Taupo Volcanic Zone. Many of the deposits contained clasts with abundant juvenile/primary textures, and initial suspicions were that these were deposits from relatively young PDCs. However PDC deposits have significant textural variability (Branne and Kokelaar, 2002; Brown and Andrews, 2015), and often require detailed fieldwork over different outcrops to make confident interpretations. The poorly exposed, small and patchy deposits at Ruapehu were difficult to confidently attribute to PDCs and could just as easily be attributed to other volcaniclastic processes that reworked erupted material. While historical phreatic and phreatomagmatic eruptions at Ruapehu have frequently produced dilute PDCs (Nairn et al., 1979; Kilgour et al., 2010), hazardous longer-runout concentrated PDCs (“pyroclastic flows”) have not been historically described and few examples are known in Ruapehu’s deposit record (Donoghue et al., 1995). Therefore, identifying young pyroclastic flow deposits at Ruapehu is essential to properly characterize the hazard.

2 TERMINOLOGY

A wide range of terms have been applied to primary and reworked volcaniclastic deposits and their components (see White and Houghton, 2006), including pyroclastic deposits containing explosively fragmented material (Wentworth and Williams, 1932; Fisher, 1966; Fisher and Schmincke, 1984), autoclastic deposits containing material fragmented at the surface of moving lava (McPhie et al., 1993; White and Houghton, 2006), and epiclastic deposits containing material fragmented by (McPhie et al., 1993) and/or transported and deposited by

non-volcanic surface processes (Cas and Wright, 1987). On volcanic edifices, these deposits usually contain either juvenile material derived directly from erupting magma, or lithic material derived by fragmentation of pre-existing material. Combining several earlier classifications, White and Houghton (2006) introduced the term “primary volcaniclastic” to describe deposits where particles are mobilized directly by explosive or effusive volcanism and not stored prior to arriving at the deposition site. However, even this broad classification introduces difficulties when interpreting ancient deposits. For example, following a large eruption much of a volcanic edifice may be covered in juvenile-textured volcanic material that can then be reworked for years after the eruption has ended (e.g., Pinatubo; Gran and Montgomery, 2005). The resulting deposits would not be primary volcaniclastic; however in proximal-medial locations (i.e., within the main volcanic edifice) where short transport distances provide little opportunity for clast modification or sorting, these deposits can be difficult or impossible to distinguish from primary deposits that were emplaced at the time of eruption. Hence almost all of the current classification schemes require at least limited interpretation of the source and mode of particle fragmentation, as well as the transport and depositional processes, and the timing of the events that formed the deposits. In proximal-medial volcanic locations where almost all material begins with an eruptive origin, such knowledge is often impossible, and the same outcrop may be interpreted in different ways by different observers. Therefore for deposit identification purposes, it is preferable to avoid any initial interpretation altogether and only assign genetic names after the most likely depositional process has been assessed. Hence, in the assessment method introduced here, we start by treating all fragmental deposits on a volcanic edifice as only “volcaniclastic deposits” until their possible origin has been evaluated.

3 PYROCLASTIC DENSITY CURRENTS AND THEIR DEPOSITS

Pyroclastic density currents are dangerous mass flows of erupted materials and gas that caused 49% (44,928) of all recorded volcanic deaths in the 20th century (Witham, 2005). They can be generated by any process that results in gravitational collapse of erupting volcanic material; including collapsing eruption columns and “boiling over” style eruptions, gravitational or explosive collapse of lava domes (Boudon et al., 1993; Calder et al., 1999; Saucedo et al., 2004; Cronin et al., 2013), collapsing lava flows (Saucedo et al., 2002; Belousov et al., 2011), or co-eruptive remobilization of erupted material falling on steep slopes (Yamamoto et al., 2005). In general, PDCs contain particles that are hotter than the ambient environment, though “cold” PDCs generated by phreatic eruptions can contain material well below magmatic temperatures (Lube et al., 2014).

PDCs form a continuous spectrum from highly mobile, dilute currents dominated by fluid turbulence (traditionally termed pyroclastic surges), to concentrated currents (pyroclastic flows) that have higher basal particle concentrations and are dominated

by particle collisions near the lower flow boundary (Branney and Kokelaar, 2002; Sulpizio et al., 2014). In practice the same PDC can exhibit both flow-like and surge-like characteristics at different points in space and time, and as such the cover-all term pyroclastic density current is generally used. However, the concentrated and dilute end-members typically produce very different deposits, and the distinction is also significant from a hazards perspective due to differences in their particle concentrations and mobility (Nakada, 2000; Valentine and Fisher, 2000). Small-volume dilute PDCs are frequently generated by phreatic or phreatomagmatic eruptions (e.g., Kilgour et al., 2010), as well as being generated by separating from moving pyroclastic flows. These energetic currents can overtop local topography, but the area impacted by them is often limited to only a few kilometers from their source (vent or basal avalanche) due to their lower momentum and density (Nakada, 2000). Dilute PDCs typically produce thin, fine-grained deposits that may have limited preservation potential in the long-term volcanic record (Kilgour et al., 2019). In contrast, concentrated PDCs are usually valley-confined and can have runout distances that extend well beyond the main edifice (Crandell, 1987). They are typically accompanied by an overriding dilute component that can separate from the main flow, further increasing the hazard (e.g., Yamamoto et al., 1993; Cole et al., 1998; Cronin et al., 2013). They therefore represent a major threat to life and infrastructure. Concentrated PDCs typically produce massive, poorly sorted deposits that can be difficult to distinguish from deposits from other volcanic mass flows. Hence for the deposit assessment purposes outlined here, the distinction between flow-like and surge-like PDCs is important and we use the legacy terms “pyroclastic flow” and “pyroclastic surge” to describe the dominant process contributing to the observed deposits. Because of the potentially greater extents and hazards associated with pyroclastic flows, and their apparent under-representation in previous studies at Ruapehu, it is these deposits that are the focus of the assessment scheme presented here.

3.1 Deposit Characteristics

Pyroclastic flow deposits span an extensive array of textures (Wilson and Walker, 1982; Branney and Kokelaar, 2002; Brown and Andrews, 2015) depending on factors including the generation mechanism and nature of the source material (e.g., Saucedo et al., 2010), transport parameters (particle concentrations, channelization and avulsion (e.g., Cronin et al., 2013), interaction with topography (Sulpizio et al., 2008), particle entrainment (Roche et al., 2013), abrasion (Dufek and Manga, 2008) and comminution (Manga et al., 2010)), and depositional variables (en-mass vs. progressive deposition (Branney and Kokelaar, 1992) diachronous deposition (Brown and Branney, 2004), deposit temperature, welding and outgassing (Wright and Cashman, 2014)). Furthermore, post-deposition alteration, and erosion and winnowing of fine material can continue to affect the preserved deposit textures even if parts of the deposit remain in-situ, while more extensive reworking can produce new volcanoclastic deposits containing similar components to the original PDC (e.g., Donoghue et al., 1999; Sarocchi et al., 2011).

In general, these processes all combine to produce poorly sorted accumulations of material that contain abundant clasts attributable to a single eruption. However, in proximal locations where all material has a volcanic origin, other volcanic mass flows, glacial processes, mass wasting, and even vent-proximal tephra can all produce texturally similar deposits.

The difficulties in distinguishing proximal-medial (i.e., within the main edifice) pyroclastic flow deposits from other volcanoclastic deposits have been frequently described. Several authors have commented on the similarities between pyroclastic flow and debris flow deposits (e.g., Fisher and Schmincke, 1984; Cas and Wright, 1987; Lerner et al., 2018), and these can be challenging to differentiate in proximal locations. Small-volume block and ash flow deposits (e.g., Saucedo et al., 2004) and debris flow deposits are both typically distributed along drainages, and unconsolidated PDC deposits are then readily remobilized as debris flows (e.g., Davila et al., 2007) containing similar components. Likewise, pumice-rich debris flows (e.g., Bond and Sparks, 1976) and proximal fallout containing ballistically-emplaced clasts can both produce deposits that are texturally similar to pumice-rich pyroclastic flow deposits. Even glacial moraines, which are extensive features on many tall stratovolcanoes, are difficult to distinguish at an outcrop scale from some pyroclastic flow and debris flow deposits (e.g., Hackett, 1985; Cowlyn, 2016).

Evidence of high temperatures (e.g., presence of charcoal, aligned clast magnetic fabric, intact but friable thermally jointed clasts, welding) at the time of deposition is one of the more reliable ways to distinguish pyroclastic flow deposits from other volcanoclastic deposits (Crandell, 1971; Uehara et al., 2015; Lerner et al., 2018; Lerner et al., 2019), especially if the deposit geometry (e.g., channelized deposit) or distance from source rule out hot vent-proximal tephra. Platz et al. (2007, 2012) used aligned magnetic fabric to help identify pyroclastic flow deposits at Taranaki volcano (NZ), but this can be difficult at volcanoes with lower concentrations of magnetic minerals like Ruapehu (Cowlyn, 2016). Furthermore, some pyroclastic flows are relatively cool at deposition and do not preserve high-temperature textures, while co-eruptive debris flows have also been known to contain hot pyroclasts (Mullineaux and Crandell, 1962; Arguden and Rodolfo, 1990). Debris flow deposits can even contain charcoal (Crandell 1987), especially where the debris flows remobilize unconsolidated deposits of earlier pyroclastic flows. There is also evidence that chemically acquired remnant magnetisation can in some instances mislead field magnetometer results (Donoghue et al., 1999), so in the absence of unequivocal high temperature evidence (e.g., welding) it is helpful to document as many different lines of high-temperature evidence as are observed.

In light of the difficulties outlined above, distinguishing pyroclastic flow deposits from other volcanoclastic deposits usually relies on the judgment and experience of the observer to weigh the field evidence and make an interpretation. This is an essential component in any geological fieldwork, but individual expert opinions do not necessarily provide consistency (e.g., Aspinall, 2006; Aspinall, 2010). Several authors (Fisher and

	Lahars	Till (excluding water-laid till)	Unwelded ignimbrite	Fluvial deposits
Large fragments (>2mm)	May have boulders weighing many tons	May have boulders weighing many tons	Extremely large boulders absent	Extremely large boulders rare
Sorting	Poor. May contain abundant clay-size material	Poor. May contain abundant clay-size material	Poor. Clay-size material rare or absent	Poor to good. Clay-size material sparse
Grading	Commonly reverse. May be normal or absent	Commonly absent	Commonly absent, but may be normal or reverse	Commonly normal
Bedding and thickness	Commonly very thick with vague internal bedding	Very thick. Bedding poor or absent	Commonly very thick with vague internal layering	Thin with channels and cross beds. Shingled gravels
Composition	Commonly 100% volcanic. May be pyroclastic or mixed with epiclastic materials. May contain bread crust bombs	Commonly heterolithic with admixtures from many sources. Plutonic, metamorphic and sedimentary clasts commonly more abundant than pyroclasts	Pyroclastic. May contain abundant bread crust bombs	Material usually 100% epiclastic except in areas of active volcanism
Rounding of large fragments	Commonly angular to subangular	Commonly faceted subangular to subrounded. May be faceted with striations and chatter marks	Commonly subangular	Commonly subrounded to rounded
Carbonaceous matter	Uncharred to charred	Uncharred	Charred	Uncharred if present
Pumice	Common in some lahars	Not present except on active volcanoes	Common	Not present except in areas of active volcanism
Distribution	In valleys spreading onto flat piedmont surfaces	Plains and valleys. May mantle all surfaces. Moraines with steep fronts	Lower parts of valleys and flat piedmont surfaces	Confined to valleys
Lower surfaces	Commonly not erosional	Erosional. Commonly rests on striated bedrock	Commonly not erosional	Erosional

FIGURE 1 | Example of an identification table for different volcanoclastic deposits adapted from Fisher and Schmincke (1984). The overlain boxes highlight the similarities between the identifying criteria, making it difficult to confidently distinguish between the different deposits. Adapted by permission from Springer Nature: Springer, Berlin, Heidelberg, Pyroclastic Rocks by Fisher, R.V. and Schmincke, H.-U., COPYRIGHT 1984.

Schmincke, 1984; Crandell, 1987) have produced tables of key deposit characteristics that are helpful for guiding field observations and making informed interpretations. However these identification tables usually present considerable overlap in deposit characteristics across different volcanoclastic deposit types, making confident deposit identification difficult (Figure 1). This is especially the case for small or poorly exposed deposits that may not contain definitive identifying textures. A further drawback of traditional identification tables is that they indirectly lead the user toward making a single definitive interpretation that does not then acknowledge the underlying uncertainties and confidence in the interpretation. A consequence of these

uncertainties is that many small or poorly exposed volcanoclastic deposits may simply be overlooked or ignored in favor of better preserved deposits. However, when investigating the frequencies and characteristics of volcanic hazards, it is important to identify as many deposits as possible irrespective of deposit size or preservation state.

4 METHODS

In order to investigate pyroclastic flow deposits at Ruapehu, we developed a novel system for quickly and consistently assessing

Deposit Characteristic	Rationale	ERUPTION-DRIVEN										WATER-TRANSPORTED				COLLAPSE-DRIVEN		GLACIALLY-TRANSPORTED		WIND-TRANSPORTED		ASSESSMENT CRITERIA		
		Concentrated FDC (Flow)	Dilute FDC (Surge)	Spatter	Fall (cent. proximal)	Fall	Lava Breccia	Debris Flow / Lahar	Fluvial	Lacustrine	Debris Avalanche	Rockfall and Small Avalanches	Moraine	Aeolian	Particularly useful for?	A. Useful as a standalone criteria? (Yes = +2, No = 0)	B. If present in original deposit, will be observed in most outcrops regardless of scale or preservation state? (Yes = +1, No = 0)	'Usefulness' Score = A + B						
DEPOSIT LAYERING	Individual thick layer (>2m)	Shows a large-scale event	Maybe: Common but not essential	No: Typically thinner and often part of stratified deposit	Maybe: Common but not essential	Maybe: Common but not essential	No: Usually thinner	Maybe: Common but not essential	Maybe: Common but not essential	No	No	No	No	No	No	No	No	No	No	Helps distinguish between surge and flow, but thin flow deposits do also occur	No: Many processes can produce both thicker or thinner deposits	Yes	1	
	Layer a part of stratified deposit with multiple laterally similar thin layers (less than 10% of one)	Shows repeating events or transport in a dilute FDC	No	Yes	Maybe	Maybe	Yes: Single eruption may produce only one layer, but perhaps from multiple eruptions frequently appear in sequence	No	No	Yes	No	No	No	No	No	No	No	No	Maybe: Can occur following very long term deposition of fine material	Helps distinguish between surge and flow otherwise similar deposits	Yes: Essentially rules out flow	Yes	1	
LAYER GEOMETRY	Layer maintains clearly undulating topography with steep thickness if sufficient bedding to see this	Characteristic of deposits formed by vertical settling as opposed to lateral transport	No	Maybe: At outcrop scale thickness variations may not be apparent	Yes: Can also be present on steep slopes	Yes: Typically clast supported	Yes	No	No	No	No	No	No	No	No	Maybe	No	Maybe	Distinguishes vertical settling processes vs lateral transport	Essentially rules out flow and strongly indicative of fall	No	2		
	Channel or valley filling geometry (if observable at this scale) and/or rapid lateral changes in thickness	Characteristic of deposits formed by topographically constrained lateral transport	Yes: but may not be apparent in a single outcrop. Flat topped deposit ponds in valleys and may veneer ridge crests due to high mobility	No	No	No	Maybe	Yes: but may not be apparent in a single outcrop.	Yes: Typically channelled	No	Maybe	Maybe	Maybe: Likely to form positive topography rather than fill channels but the distinction may not be observable at outcrop scale	No	No	No	No	Maybe	Distinguishes channelled vs non-channelled transport	Yes	No	2		
	Deposit forms a hummocky (with significant topography features) on its upper surface	Characteristic of deposits formed by en-masse transport	No	No	No	No	No	No	No	Yes: Hummocky topography is characteristic of debris avalanche deposits	Maybe	Yes: Moraines create positive relief and may appear as hummocks	No	No	No	No	No	No	Maybe	This is a key characteristic of debris avalanche deposits	Yes: Strongly suggests debris avalanche	No	2	
LAYER GRADING	Normal coarse-tail grading of lithic fraction	Coarse-tail grading means only the larger clasts are graded, often in a finer ungraded matrix. This typically occurs during transport in a higher particle concentration flow	Yes: Common characteristic	Maybe	No	No	No	No	No	Maybe	Maybe	No	No	No	No	No	No	No	No	Yes: Indicative of dense FDC	Yes	3		
	Reverse coarse tail grading of clasts	Coarse tail grading means only the larger clasts are graded, often in a finer ungraded matrix. This typically occurs during transport in a higher particle concentration flow	Yes: Common characteristic	Maybe	No	No	No	No	Maybe	Maybe	No	No	No	No	No	No	No	No	No	Yes: Strongly indicative of dense FDC	Yes	3		
	Distinct fine grained base below coarser deposit	Deposition of a finer grained base	Maybe	Maybe	No: Only if changes in eruption intensity produced this	No: Only if changes in eruption intensity produced this	No: Only if changes in eruption intensity produced this	No	Yes: Common characteristic	No	No	No	No	No	No	No	No	No	No	Debris flows	Yes: Strongly suggests debris flow	Yes	3	
	Reverse graded near base	Basal reverse grading can occur during lateral transport in a FDC or debris flow.	Maybe	Maybe	No: Only if changes in eruption intensity produced this	No: Only if changes in eruption intensity produced this	No: Only if changes in eruption intensity produced this	No	Yes: Characteristic of changes in flow (debris flows not containing juvenile)	Maybe: If changes in flow intensity produced this juvenile	No	No	No	No	No	No	No	No	No	Yes: Indicative of debris flow	Yes	3		
	Normally graded near top	Suggests waning transport capacity at end of deposition	Maybe	Maybe	No: Only if changes in eruption intensity produced this	No: Only if changes in eruption intensity produced this	No: Only if changes in eruption intensity produced this	No	Yes: Characteristic of changes in flow (debris flows not containing juvenile)	Maybe: If changes in flow intensity produced this juvenile	No	No	No	No	No	No	No	No	No	No	No	0		
LAYER BEDFORMS / TRANSPORT FEATURES	Fluvial type bedforms (steep cross beds, ripple)	Typically occur during fluvial transport	No	No: May appear similar but generally lower angle and longer wavelength	No	No	No	No	No	Yes	Maybe: Typically finer material	No	No	No	No	No	No	Maybe: Can appear very similar. Cross beds at angle of ripple	Fluvial deposits	Yes	Yes	3		
	Characteristic surge bedding (lenses, antidunes, low angle cross beds, pinch and swell bedding)	Typically occur during energetic low particle concentration FDC and swirl bedding	No	No	No	No	No	No	No	No	Note: it can appear similar	No	No	No	No	No	No	No	Surge deposits	Yes	No	2		
	Evidence of lateral transport of significant quantities of large bomb-like clasts (e.g. discontinuous lenses, tabulation)	Shows deposit was formed from a current with significant transporting power	Yes	Maybe: Surges tend to be finer grained	No	No	No	Yes	Yes	Maybe: Typically finer material	Maybe: Mostly moves as more coherent mass	Yes	Maybe	No	No	No	No	No	Shows deposit was formed from a current with significant transporting power	Yes	No	2		
	Coherent patches of the deposit maintaining some element of pre-transport stratigraphy	Shows that significant parts of the material moved together in-mass from source to deposition. Ideally need to observe several such clasts	No	No	No	No	No	No	No	No	No	Yes: Megablocks, coloured zones, and hummocky topography	No	No	No	No	No	No	Debris avalanches	Yes: Strongly indicative of debris avalanches	No	2		
DEPOSIT COMPONENTS	Parts of broken clasts in the deposit have remained close to each other and can be seen to fit back together (jigsaw fit)	Shows that significant parts of the material moved together in-mass from source to deposition. Ideally need to observe several such clasts	No	No	No	No	No	No	Maybe	No	No	Yes	Maybe	No	No	No	No	No	Debris avalanches	Yes: Strongly indicative of debris avalanches	No	2		
	Abundant (e.g. >50%) clasts that appear to be from the same source (e.g. mostly monomineralic, similar surface textures, colour, mineralogy, weathering)	Magnet and photomagnetic clasts produce clasts reflecting the source magma. In-vacuo eruptions sample rocks from a relatively small point source (i.e. the vent).	Yes	Yes	Yes	Yes: especially angular clasts with 'juvenile' textures	Yes: especially angular clasts with 'juvenile' textures	Yes: monomineralic	Maybe: If co-eruptive or associated with a recent eruption. Otherwise commonly heterolithic	Maybe: If co-eruptive or associated with a recent eruption. Otherwise commonly heterolithic	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Distinguishes deposits with single dominant source	Yes: A broad way of trying to separate deposits from co-eruptive processes vs longer-term volcanoclastic processes	Yes	3	
	Dominantly contains highly vesicular clasts	Vesicular clasts are characteristic of explosive volcanism	Maybe: Some types of FDC contain denser clasts or fillings	Maybe: Some types of FDC contain denser clasts or fillings	Maybe	Maybe	Maybe	No	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	Maybe: Depends on source material	No: Many clasts on a volcanic edifice are vesicular and easily transported	Yes	1			
	Abundant separate crystal fraction (not part of clasts)	Yes: Crystal content can be higher in the matrix than in the pyroclasts	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes: Indicative of FDCs	Yes	3		
DEPOSIT SORTING	Accretionary lapilli	Evidence of a "wet" eruption and likely co-eruptive transport and emplacement - the fragility of accretionary lapilli means they are unlikely to survive in fall layers following the FDC	Maybe: Not very likely to be preserved in high quantities during transport. Can be present in fall layers following the FDC	No	Maybe	Maybe	No	No: Unlikely to be preserved during transport	No	No: Has occurred (Bancroft, Oruanui deposits, NZ), but exceedingly rare	No	No	No	No	No	No	No	No	Wet vs dry eruptions	Yes: Can help distinguish between dense and dilute FDCs in otherwise similar deposits	No	2		
	Poorly Sorted / Unsorted	Distinguishes high input, transient events from longer term steady events	Yes	Maybe: Individual lamellae typically moderately/well sorted. Bulk deposit can be less well sorted	Maybe: Somewhat poorly sorted in very proximal areas	Maybe: Somewhat poorly sorted in very proximal areas	No: Moderate to good sorting should be apparent	Maybe: Somewhat poorly sorted	Yes: Can be coarser grained and more poorly sorted than pyroclastic flows.	No: Typically well sorted	No: Well sorted	Yes	Yes	Yes	Yes	Yes	Yes	No: Typically well sorted	Identifying high input transient events	Yes: Broadly separates high input transient events from longer term volcanoclastic processes	Yes	3		

FIGURE 2 | Key deposit characteristics resulting from most common volcanoclastic processes. Criteria are assessed on their usefulness as standalone criteria for identifying particular volcanoclastic processes (scored from 0 to 2), and on their ability to be observed in any deposit (scored from 0 to 1). Highlighted criteria, including all criteria with a total 'usefulness' score ≥ 2 are included in the final assessment scheme (**Figure 3**). (Synthesized from the field experiences of the authors and Aramaki and Akimoto, 1957; Parsons, 1969; Johnson, 1970; Crandell, 1971; Walker, 1971; Sparks and Walker, 1977; Hoblitt and Kellogg, 1979; Wilson, 1980; Fisher and Schmincke, 1984; Cas and Wright, 1987; Crandell, 1987; McPhie et al., 1993; Druitt, 1998; Freund et al., 2000; Branney and Kokelaar, 2002; Capra and Macias, 2002; Bernard et al., 2009; Sarcocchi et al., 2011; Brown and Andrews, 2015; Lerner et al., 2018; Saucedo et al., 2019).

the possible origins of the different volcanoclastic deposits observed. The aim of this system was to distill the reasoning of an experienced field geologist into a more structured and repeatable method for assessing candidate pyroclastic flow deposits, and at the same time explicitly address any interpretative uncertainty. This follows four principles:

- (1) To identify deposit features that directly support or oppose an interpretation that the deposit was emplaced by a pyroclastic flow.
- (2) To identify deposit features that might instead suggest the deposit was emplaced by other volcanoclastic processes, and hence challenge a pyroclastic flow interpretation.

	Abundant bomb-sized clasts	Distinguishes higher vs lower energy processes	Yes Typically abundant	Maybe: Mostly ash and/or lapilli	Yes	Yes	No: Typically mostly lapilli or ash further from source	Yes	Yes: Common, can exceed 1m	No	No	Yes	Yes	Yes	No	Identifying higher energy processes	No	Yes	3
CLAST SIZES	Mostly ash or lapilli-sized clasts	Reflects either finer material at source (e.g. from phreatomagmatic fragmentation), lower energy erosion and transport processes (e.g. fluvial, aeolian), or size fractionation with greater distances from source (e.g. lapilli).	Maybe: Especially with increasing distance from source	Yes	No: Unlikely to have bombs	No: Unlikely to have bombs	Yes	No: Many bomb-sized clasts	Maybe	Yes	Yes: Often very fine	No	No	No	Yes: Typically very fine	No	Yes	3	
	Flow-grained matrix within coarser deposit	Shows very poor sorting during transport, which typically occurs during higher particle concentration transport	Yes: Typically poorly sorted. But absence of fines does not preclude a PDC origin	Maybe: Whole deposit is often finer grained ash and lapilli	No	No: Clast supported with limited fines	No: Clast supported with limited fines	No: Low proportion of material finer than 2mm. May have cone framework	Yes: Silt/clay size fraction may be present. Absence of fines does not preclude a debris flow origin	No: May contain abundant fine material, but typically well-sorted	No: May contain abundant fine material, but typically well-sorted	Yes	No: Clast supported	Maybe: Poorly sorted deposit with range of grain sizes	No: Whole deposit is likely to be very fine grained	Showing high particle concentration transport	Yes	Yes	3
CLAST TEXTURAL FEATURES	Most clasts have a clear skin or chilled margins that extend around the entire clast	This typically forms on clasts preserved around the entire clast. It suggests the clast has not broken since skin formation (during transport)	Maybe: May not be observable, and PDC deposits from phreatic explosions may not have chilled margins	Maybe: Clasts may appear to have a 'skin' but not a pronounced chilled margin	Maybe: Clasts may not be observable, and PDC deposits from phreatic explosions may not have chilled margins	Maybe: Clasts may not be observable, and PDC deposits from phreatic explosions may not have chilled margins	Maybe: Clasts may appear to have a 'skin' but not a pronounced chilled margin	Maybe: Clasts may appear to have a 'skin' but not a pronounced chilled margin	Maybe: Depends on source material	Maybe: Depends on source material	No: Likely too fine grained to observe	No: Clasts are broken from source rock	Maybe: Depends on source material	No: Likely too fine grained to observe	Showing the clast was originally hot (i.e. emplaced) and has not broken since it cooled. Implies only limited reworking if any.	Yes	Yes	3	
	Isolated clasts (from abrasion during transport) in the deposit	Orients form as clasts are dragged against other rocks during transport	Maybe: Unlikely to be abundant	No	No	No	No	Maybe: Unlikely to be abundant	No	No	No	No	No	Maybe: Unlikely to be abundant	No	No	No	No	0
DEGASSING / DEWATERING	Most clasts are abraded/rounded (noting that deposit is in proximal-medial location)	Suggests transport with significant particle collisions to produce rapid rounding.	Yes: Some rounding during transport	No	No	No	No	Yes: Some rounding during transport	Yes: Some rounding during transport	Yes: Very fine grained	Maybe: Depends on source material rather than scouring during transport	No: Generally angular	Maybe: Depends on source material	Maybe: Some rounding during transport. Very fine grained	No	No	No	4	
	Estratification / openwork apices (can be depleted in fines and enriched in crystal or lithic component)	Degassing structures are characteristic of PDC deposits	Yes: Very characteristic of PF deposits	Maybe	No	No	No	No	Maybe: May have degassing or gas escape structures	No	No	No	No	No	Dense PDCs	Yes	No	2	
EVIDENCE OF HIGH TEMPERATURES DURING/AFTER TRANSPORT	Primarily fractured small bomb-sized clasts (i.e. clast is still as together)	Prismatic fracturing occurs as hot clasts cool. If this happens during transport the clast should then break apart. Therefore indicate the clast remained hot at the time of deposition. Smaller bombs suggest the whole deposit was emplaced hot, whereas larger bombs could remain hot even when transported in a cooler fluid	Yes	Maybe	Yes	Maybe	No	Yes	No: 'Hot' lahars can occur, and larger clasts in particular may retain their heat. Smaller clasts will typically cool before deposition	No	No	Maybe: Can occur if pyroclastic material was involved in the debris avalanche	No	No	Distinguishes high deposit temperatures at the time of deposition	Yes	Yes	3	
	Presence of charcoal fragments incorporated into the deposit	Charcoal is evidence of high temperatures, while incorporation into the deposit suggests later transport. However charcoal can be easily reworked (e.g. from a nearby PDC deposit) and incorporated into other deposits, but may not survive extensive reworking	Yes: Although many tall or stovetop cones lack significant vegetation in proximal-medial areas	Maybe	No	No	No	No	Maybe: Wood is more likely to be charred than charcoalized. Charred wood may be present if next to a large clast. Clast charcoal may be present if the debris flow reworked PDC deposits	Maybe: If reworking PDC deposits	No	No	No	No	Yes: With the caveat that charcoal can be easily reworked. But nonetheless implies there was a high-temperature deposit emplaced nearby	No	No	2	
	Widespread pinking or reddish-grey deposit alteration (not just individual clasts), particularly at the top of the deposit	Evidence of high deposit temperatures after deposition	Yes: Characteristic of PF deposits	No: Not likely due to fine grain sizes and thin layers	Maybe: Clasts can be oxidized red but this can occur prior to deposition	Maybe: Clasts can be oxidized red but this can occur prior to deposition	Maybe: Clasts can be oxidized red but this can occur prior to deposition	Maybe: Clasts can be oxidized red but this can occur prior to deposition	No	No	No	No	No	No	Distinguishes high deposit temperatures at the time of deposition	Yes	No	2	
OTHER	Magnet magnetic fabric of clasts determined by possible magnetometer	Shows that the deposit was emplaced at temperatures above the Curie point of the magnetic minerals.	Yes: However not all PDCs will be emplaced above the Curie point of their magnetic minerals.	Maybe	Yes: Should be relatively preserved to a possible vent	Maybe	No	Yes	Maybe: Debris may carry hot clasts and produce similar results, but more usually have randomly aligned NRM, or may have a lower proportion of clasts showing aligned NRM.	No	No	Maybe: Can occur if significant pyroclastic material was involved in the debris avalanche	No	No	Distinguishes high deposit temperatures at the time of deposition	Yes	Yes	4	
	Deposit welding	Shows the deposit was emplaced at high enough temperatures to fuse its components	Yes: Characteristic feature if present, but many pyroclastic flows are un-welded. Can be welded a long way from possible source	No	Yes: Should be relatively preserved to a possible vent	Maybe	No	Yes: No	No	No	No	No	No	Distinguishes high deposit temperatures at the time of deposition	Yes	Yes	3		
OTHER	Deposit location in relation to other deposits or features	Surrounding features may help identify or eliminate different processes	Deposit does not need to be located close to a plausible source for the main clast types	Located near a plausible vent source	Located near a plausible vent source	Commonly associated with a larger sequence of other distal tephra	Associated with low flow cores.	Deposit does not need to be located close to a plausible source for the main clast types	Associated with other fluvial/lacustrine deposits	Associated with other fluvial/lacustrine deposits	Deposit does not need to be located close to a plausible source for the main clast types	Associated with other fluvial/lacustrine deposits	Associated with other fluvial/lacustrine deposits	Associated with other fluvial/lacustrine deposits	N/A	Yes: Evidence from the surrounding environment should always be considered	No	2	

FIGURE 2. | (Continued).

- To use (1) and (2) to assess the confidence by which the deposit can be interpreted to have been emplaced by a pyroclastic flow, and to compare that to the confidence by which it may be interpreted to have been emplaced by other processes.
- Where the deposit features can be explained by more than one volcanoclastic process, to recognize there is uncertainty in the interpretation and therefore to identify the process(es) that may best explain the observed features.

In practical terms, certain criteria are more useful than others when initially assessing a deposit's origin. For example, a deposit containing abundant vesicular clasts could have been emplaced by any volcanoclastic process since there is often abundant vesicular material available for reworking on a volcanic edifice. Hence the presence of vesicular clasts, by itself, would not significantly help identify a deposit's origin. In contrast, a welded volcanoclastic deposit could only have been emplaced by

“hot” volcanoclastic processes such as proximal spatter/tephra or pyroclastic flows. The presence of welding alone would therefore rule out “cold” volcanoclastic processes irrespective of any deposit textures that may otherwise support them, and hence would greatly focus the interpretation. An experienced field geologist intuitively uses the most indicative features to focus their initial assessment, and this is something we aim to replicate in the assessment scheme. Therefore to identify the most “useful” criteria for assessing pyroclastic flows and other common volcanoclastic deposits, we first compiled a list of characteristic outcrop-scale deposit features (Figure 2 and digital appendix). We then focused on those criteria that:

- Identify deposits that are more likely to have been emplaced directly during an eruption (i.e., similar to White and Houghton's (2006) “Primary Volcanoclastic”)
- Are likely to be observable in most outcrops irrespective of outcrop size or preservation state.

- (3) Are particularly useful as standalone criteria to identify specific volcanoclastic processes, especially where the feature helps support or oppose an interpretation of deposition from a pyroclastic flow.

After focusing and combining similar criteria from **Figure 2**, a shortlist of 15 criteria were identified for use in the final assessment scheme.

5 A CONFIDENCE-BASED METHOD FOR ASSESSING CANDIDATE PYROCLASTIC FLOW DEPOSITS

The new system for assessing candidate pyroclastic flow deposits is presented in **Figure 3**, and also as an excel worksheet in the digital appendix. A glossary for the assessment criteria is provided in **Appendix 1**. It is important to note that the assessment scheme's observational criteria are tailored specifically for assessing whether the deposit features are consistent with deposition by a pyroclastic flow, and are not intended as an in-depth assessment of other volcanoclastic deposits. It is assumed that the deposit is located on/near a volcanic source and within the reasonable range of PDCs.

The assessment begins with two observations that can be determined in every deposit regardless of size or state of preservation. The first, "does the deposit contain >50% compositionally and texturally similar volcanic clasts," identifies deposits that are mostly homogenous, and hence reflects a dominant particle source. This is consistent with (but not limited to) deposits emplaced during or shortly after an eruption. It is therefore similar to White and Houghton's (2006) "Primary Volcanoclastic" classification, but recognizes that erupted material does not always have juvenile clast textures, and that primary deposits can be difficult to distinguish from secondary reworking of freshly erupted material.

The second observation considers whether the deposit has poor vs. moderate/good sorting. This distinguishes between deposits from transient, high energy and high particle concentration events like pyroclastic flows, and those from steadier and typically lower energy and lower particle concentration processes whose clasts become better sorted during transport. Together, the first two observations focus the assessment into three categories that broadly distinguish the most likely volcanoclastic processes to have formed the deposit in each case. These are:

- (1) Heterolithologic deposits: Heterolithologic deposits cannot confidently be associated with an eruption, so are considered "unlikely" to have been emplaced by a pyroclastic flow. The most likely types of heterolithologic deposits are fluvial, lacustrine and eolian deposits, glacial moraines, debris flow and debris avalanche deposits, and phreatic tephra (including phreatic surges).
- (2) Homogenous, poorly sorted deposits: Homogenous deposits might be associated with an eruption and so it is possible they were emplaced by a pyroclastic flow. The most likely types of poorly sorted homogenous deposits are

pyroclastic flow deposits and the more poorly sorted surge deposits, co/post-eruptive debris flow deposits, proximal fall deposits, lava breccias, rockfall deposits, and post-eruptive moraines.

- (3) Homogenous, moderately/well sorted deposits: Homogenous deposits might be associated with an eruption and so it is possible they were emplaced by a pyroclastic flow. However, pyroclastic flow deposits are typically poorly sorted. The most likely types of moderately/well sorted homogenous deposits are fall deposits, better sorted pyroclastic surge deposits, and post-eruptive fluvial, lacustrine and aeolian deposits.

While deposits from different volcanoclastic processes will not always fit neatly into these categories, the categories are sufficiently characteristic that their presence or absence strongly influences the confidence in a given interpretation. For example, it would be difficult to confidently attribute a poorly sorted deposit to low-energy fluvial processes, or to interpret a heterolithologic deposit as a lava breccia. Therefore, the three categories sufficiently focus the range of possible interpretations that the remaining assessment criteria can then function as independent (standalone) items which by themselves either support emplacement from a particular volcanoclastic process, or oppose it and eliminate that process from further consideration. However, unlike the first two criteria which can be assessed for any deposit irrespective of size or preservation state, the remaining 13 criteria are process-specific and hence only some of these apply for any given deposit. As such, only those that are actually observed in the deposit are used for the final assessment.

5.1 Assigning Confidence Scores

In order to assess which volcanoclastic process(es) are most likely to have formed a given deposit, the user first determines which of the 13 standalone criteria are present in the deposit, placing a tick next to each that applies. These 13 criteria are associated with a series of pre-assigned values, assigned by the authors, that show how indicative each criteria is of deposits from the different volcanoclastic processes (Boxes A and B, **Figure 3**). Values 1–4 mean the criteria sometimes occurs in deposits from the relevant process, with 1 meaning it is not strongly indicative (i.e., the feature's presence does not strongly support that volcanoclastic process) and 4 meaning it is very strongly indicative (i.e., the feature's presence strongly supports that process). A value of 5 means that the criteria opposes emplacement by that process, eliminating it from further consideration. So, for example, the first three indicative values for the criteria "layer is part of a stratified deposit with multiple thin layers" (**Figure 3**) are:

	Pyroclastic Flow	Surge	Spatter	...
Stratified deposit	5	3	2	...

This in essence states that thinly stratified layering is unlikely to occur in deposits from pyroclastic flows (5), strongly indicative of deposits from surges (3), and can occur in spatter deposits but

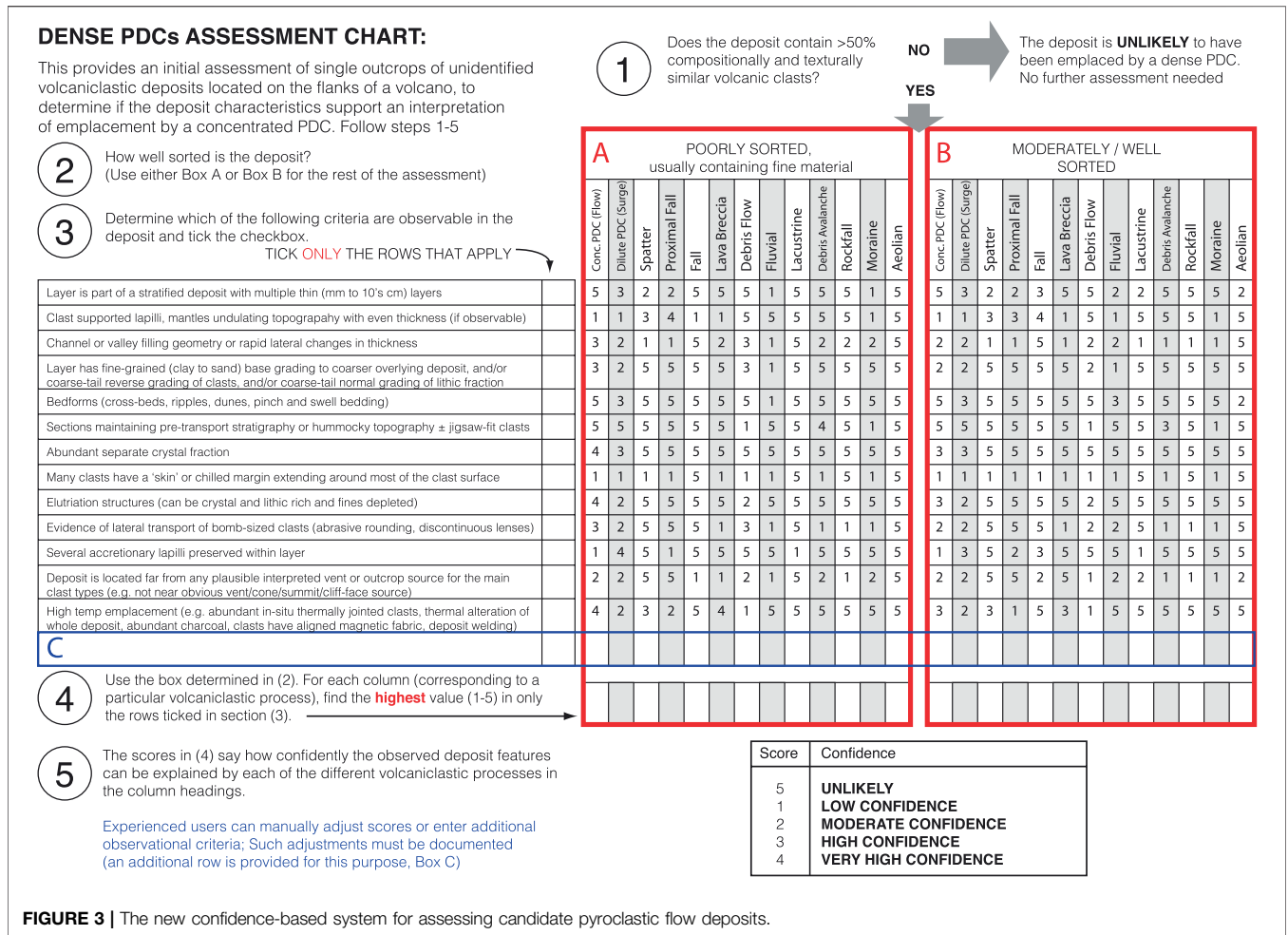


FIGURE 3 | The new confidence-based system for assessing candidate pyroclastic flow deposits.

is not as indicative (2). Because several of the 13 standalone criteria may be present in any given deposit, their respective indicative values then need to be combined to determine the deposit's overall "score." Here, the highest indicative value for each volcanoclastic process is the one used. Hence, if a deposit is both "stratified" and has "evidence of high temperature emplacement" (i.e., 2 of the 13 standalone criteria) then their first three indicative values and final assessment scores are:

	Pyroclastic Flow	Surge	Spatter	...
Stratified deposit	5	3	2	...
High temperature	4	2	3	...
Final score	5	3	3	...
—	Unlikely	High	High	...

Carrying forward the highest values reflects the standalone nature of each of the 13 criteria - that is to say that for each of the criteria observed in the deposit, it is the criteria that most strongly points to emplacement by a particular process that supersedes other criteria that are less strongly indicative. This is also why the highest indicative value (5) is assigned when a criteria opposes emplacement from a particular process, since

any observation that eliminates a process must supersede any other criteria that might support it. The resulting final assessment scores therefore reflect how indicative all of the observed criteria, taken together, are of emplacement by each of the different volcanoclastic processes. As such, they indicate the level of confidence by which the deposit's features can be explained by each volcanoclastic process. A final score of 1–4 indicates the deposit features are consistent with emplacement from that process, at increasing levels of confidence (low, moderate, high, very high). A final score of 5 means the deposit features are unlikely to have been formed by that process. Hence in the example above, the deposit features are consistent with surge (3 = high confidence) or spatter deposits (3 = also high confidence), but are unlikely to have formed from a pyroclastic flow (5 = unlikely).

While the assessment scheme provides a rapid, standardized mechanism for assessing candidate pyroclastic flow deposits, it cannot cover every possible observational criteria and is not intended to supersede additional observations that assist the final interpretation. Therefore, more experienced users may manually adjust scores or introduce additional observational criteria, if present, that change the confidence ratings. Any such adjustments should

be documented, and if additional criteria are introduced then appropriate user-defined indicative values must be allocated in Boxes A and B. The paper chart includes a blank row for this purpose. The excel worksheet in the digital appendix automates the scoring process outlined above, and may be used in the field using freely available spreadsheet software for smartphones or tablet computers.

5.2 Application of the Method to a Volcaniclastic Deposit at Ruapehu Volcano

Fieldwork by Cowlyn (2016) identified an extensive pumiceous volcaniclastic deposit on the northern edge of Ruapehu's Mangatoetoe valley (Figure 4). Chapman (1996) had previously interpreted this deposit as a tephra-covered moraine, but acknowledged that its thick tephra cover had prevented observation of the internal fabric. Chapman's (1996) interpretation was likely guided by the overall morphology of the remaining deposit, which at its western edge superficially resembles a lateral moraine ridge and glacial close-out loop. Cowlyn (2016) later found several incised gulleys where small patches of the in-situ deposit were exposed. These showed that the deposit was dominantly composed of at least two poorly sorted volcaniclastic units containing a mix of large pumices and lithic clasts in a finer grained matrix, and separated in at least one location by a layered ash. Field observations of the lowermost unit revealed:

- The layer contains approximately 50% pumice and 50% lithic clasts for much of its thickness, but this increases to ~95% pumice at the top. The pumices are texturally and compositionally similar.
- The layer is poorly sorted, containing lapilli and bomb-sized clasts and a significant amount of ash matrix.
- Although not observable at a single-outcrop scale, the larger deposit sequence (all layers) completely fills a small palaeovalley.
- At the top of the lowermost layer the number of very large pumices increases (i.e., reverse coarse-tail grading of pumices).
- Several of the pumices appear to have been abrasively rounded.
- The deposit is ~5 km from Ruapehu's summit and not near any known vents.
- The layer is at least 10 m thick

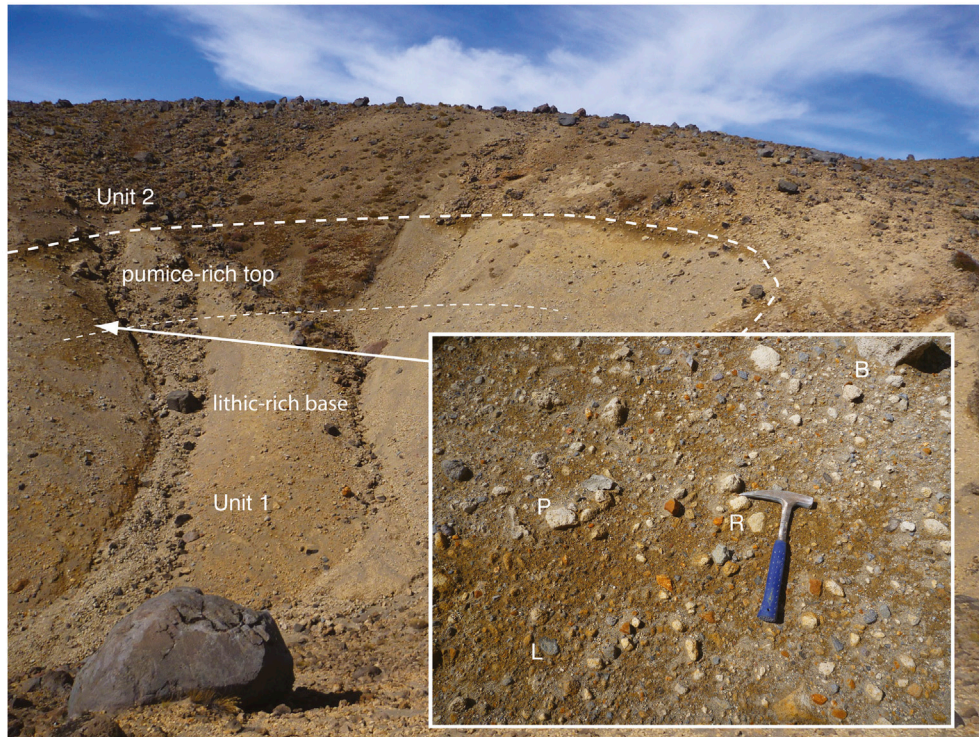
An initial field assessment (without using the assessment scheme) was that the deposit resembled a debris flow deposit that had reworked freshly erupted pumices and entrained significant amounts of lithic material. This would be a reasonable experience-based assessment, particularly in light of the high proportion of lithic material. Working through the new assessment and manually including the additional observation of the deposit's 10 m thickness, together with user-defined indicative scores for this extra criteria (Figure 4, Box C), the scheme agrees that the observed deposit features are consistent with emplacement from a debris flow at "high confidence." However, the assessment also suggests that the deposit features can be explained by emplacement from a pyroclastic flow, again with "high

confidence" (Figure 4). The assessment result therefore explicitly encourages consideration of both interpretations. In cases where it is important to definitively identify a deposit, the results of this initial assessment can inform any follow-up field or laboratory investigations (e.g., component or grain size analyses) that may then refine the interpretation. For the Ruapehu deposit, investigations with a portable fluxgate magnetometer (e.g., Platz et al., 2012) showed that many of the bomb-sized clasts had aligned magnetism consistent with hot emplacement (Cowlyn, 2016), most strongly supporting emplacement by a pyroclastic flow with a new score of 4 ("very high confidence"). At a volcano with few documented pyroclastic flows, this is an important finding, and highlights the importance of recognizing and addressing interpretative uncertainty.

6 DISCUSSION

The assessment scheme presented here is a rapid, repeatable method for assessing volcaniclastic deposits of unknown origin to determine if they may have been emplaced by a pyroclastic flow. Where possible, it uses criteria that are easily observed at single outcrops of any scale, while rarer criteria are only used to distinguish between similar deposits or increase interpretative confidence. Hence, this system can be used at any outcrop irrespective of size or preservation state, and irrespective of how many (or how few) deposit characteristics can be observed. This is advantageous, as it encourages assessment of even poorly-exposed deposits that may otherwise be overlooked. The system differs from identification tables that typically list "ideal" deposit features, as these do not address the significant variability of natural systems or acknowledge the resulting interpretative uncertainty. The new system explicitly addresses such uncertainty by identifying processes that could have produced the observed deposit and quantifying how confidently each of those processes explain the deposit features. In this way, the most likely process(es) to have formed the assessed deposit features can be identified and any final interpretation fully justified.

Instead of only looking for criteria that support emplacement by a pyroclastic flow, the assessment system actively looks for features that distinguish between these and other potentially similar deposits. In other words, the system actively considers and tries to eliminate other possible interpretations in order to increase the interpretative confidence. This, together with transparently reporting any remaining uncertainty, is a best-practice approach applicable to research investigations of all kinds. As such, the assessment scheme is useful as a teaching and discussion tool that guides students toward developing a scaffolding framework that encourages expert-like habits (Petcovic and Libarkin, 2007). It is important to remember, however, that the assessment scheme's observational criteria are tailored specifically for assessing whether the deposit features are consistent with deposition by a pyroclastic flow. As such, the assessment is not suitable for fully identifying deposits from other



DENSE PDCs ASSESSMENT CHART:

This provides an initial assessment of single outcrops of unidentified volcanoclastic deposits located on the flanks of a volcano, to determine if the deposit characteristics support an interpretation of emplacement by a concentrated PDC. Follow steps 1-5

2 How well sorted is the deposit? (Use either Box A or Box B for the rest of the assessment)

3 Determine which of the following criteria are observable in the deposit and tick the checkbox. TICK ONLY THE ROWS THAT APPLY

Layer is part of a stratified deposit with multiple thin (mm to 10's cm) layers	
Clast supported lapilli, mantles undulating topography with even thickness (if observable)	
Channel or valley filling geometry or rapid lateral changes in thickness	<input checked="" type="checkbox"/>
Layer has fine-grained (clay to sand) base grading to coarser overlying deposit, and/or coarse-tail reverse grading of clasts, and/or coarse-tail normal grading of lithic fraction	<input checked="" type="checkbox"/>
Bedforms (cross-beds, ripples, dunes, pinch and swell bedding)	
Sections maintaining pre-transport stratigraphy or hummocky topography a jigsaw-fit clasts	
Abundant separate crystal fraction	
Many clasts have a "skin" or chilled margin extending around most of the clast surface	
Elutriation structures (can be crystal and lithic rich and fines depleted)	
Evidence of lateral transport of bomb-sized clasts (abrasive rounding, discontinuous lenses)	<input checked="" type="checkbox"/>
Several accretionary lapilli preserved within layer	
Deposit is located far from any plausible interpreted vent or outcrop source for the main clast types (e.g. not near obvious vent/cone/summit/cliff-face source)	<input checked="" type="checkbox"/>
High temp emplacement (e.g. abundant in-situ thermally jointed clasts, thermal alteration of whole deposit, abundant charcoal, clasts have aligned magnetic fabric, deposit welding)	

4 Use the box determined in (2). For each column (corresponding to a particular volcanoclastic process), find the highest value (1-5) in only the rows ticked in section (3).

5 The scores in (4) say how confidently the observed deposit features can be explained by each of the different volcanoclastic processes in the column headings.

Experienced users can manually adjust scores or enter additional observational criteria; Such adjustments must be documented (an additional row is provided for this purpose, Box C)

1 Does the deposit contain >50% compositionally and texturally similar volcanic clasts? **NO** → The deposit is **UNLIKELY** to have been emplaced by a dense PDC. No further assessment needed. **YES** →

A POORLY SORTED, usually containing fine material												B MODERATELY / WELL SORTED														
Conc. PDC (Flow)	Dilute PDC (Surge)	Spatter	Proximal Fall	Fall	Lava Breccia	Debris Flow	Fluvial	Lacustrine	Debris Avalanche	Rockfall	Moraine	Aeolian	Conc. PDC (Flow)	Dilute PDC (Surge)	Spatter	Proximal Fall	Fall	Lava Breccia	Debris Flow	Fluvial	Lacustrine	Debris Avalanche	Rockfall	Moraine	Aeolian	
5	3	2	2	5	5	5	1	5	5	5	1	5	5	3	2	2	3	5	5	2	2	5	5	5	2	
1	1	3	4	1	1	5	5	5	5	5	1	5	1	1	3	3	4	1	5	1	5	5	5	5	1	5
3	2	1	1	5	2	3	1	5	2	2	2	5	2	2	1	1	5	1	2	2	1	1	1	1	5	5
3	2	5	5	5	5	3	1	5	5	5	5	5	2	2	5	5	5	5	2	1	5	5	5	5	5	5
5	3	5	5	5	5	5	1	5	5	5	5	5	5	3	5	5	5	5	3	5	5	5	5	5	5	2
5	5	5	5	5	5	1	5	5	4	5	1	5	5	5	5	5	5	5	1	5	5	3	5	1	5	5
4	3	5	5	5	5	5	5	5	5	5	5	5	3	3	5	5	5	5	5	5	5	5	5	5	5	5
1	1	1	1	5	1	1	1	5	1	5	1	5	1	1	1	1	1	1	1	1	5	1	5	1	5	5
4	2	5	5	5	2	5	5	5	5	5	5	5	3	2	5	5	5	5	5	5	5	5	5	5	5	5
3	2	5	5	5	1	3	1	5	1	1	1	5	2	2	5	5	1	2	2	5	1	1	1	1	5	5
1	4	5	1	5	5	5	5	1	5	5	5	5	1	3	5	2	3	5	5	5	1	5	5	5	5	5
2	2	5	5	1	2	1	5	2	1	2	5	5	2	2	5	5	2	5	1	2	2	1	1	1	1	2
4	2	3	2	5	4	1	5	5	5	5	5	5	3	2	3	1	5	3	1	5	5	5	5	5	5	5
C Layer is 10m thick																										
2 5 1 1 5 5 2 5 1 2 1 2 5																										
3 5 5 5 5 5 3 5 5 5 5 5 5																										

Score	Confidence
5	UNLIKELY
1	LOW CONFIDENCE
2	MODERATE CONFIDENCE
3	HIGH CONFIDENCE
4	VERY HIGH CONFIDENCE

FIGURE 4 | Example volcanoclastic deposit from Ruapehu volcano. This poorly sorted deposit contains pumice (P) and lithic (L) clasts in a fine-grained matrix. Many of the pumices are bomb-sized (B) and show signs of abrasive rounding during transport (R). The final confidence scores (Step 4) are the highest numbers from the columns above, following the process detailed in Section 5.1 of the main text. Here, the scores suggest the observed textures are best attributed to either a debris flow or a pyroclastic flow, both at "high confidence." Note the manual addition of an additional assessment criteria (deposit thickness) and associated user-generated indicative scores in Box C. This demonstrates how more experienced users can modify the scheme in light of their own observations; in this case helping to eliminate surge and fluvial deposits from the interpretation.

volcaniclastic processes. To do so would require observations of additional assessment criteria tailored specifically to those deposits. For example, the presence of “bedforms” is here sufficient to challenge an interpretation that the deposit was emplaced by a pyroclastic flow, but does not provide the necessary detail (e.g., bedform type, angle, wavelength) to correctly distinguish between fluvial or surge deposits. Therefore, when different volcanoclastic processes return higher confidence scores, this serves to show that the observed deposit features may not be best explained by deposition from a pyroclastic flow, but does not provide an in-depth assessment of the other volcanoclastic processes. Nevertheless, the basic principles governing this confidence-based approach can easily be adapted to any geological deposit assessment (not just volcanoclastic deposits) by modifying the specific assessment criteria for the required purpose.

The biggest limitation of the scheme is that 15 criteria cannot cover every possible deposit feature useful to an interpretation, and hence it cannot fully substitute for professional experience. An experienced field investigator integrates multiple lines of evidence to quickly access and assess prior knowledge (Petcovic and Libarkin, 2007) in a way that is not possible within the rigid framework of a chart or table. However the assessment scheme partially addresses this limitation by explicitly allowing the user to manually adjust the confidence ratings in light of additional observational evidence and personal experience (see example in **Figure 4**). This is not a “fudge” factor, as it still requires the user to justify and record any changes and report the adjusted confidence scores across the full range of volcanoclastic processes. Hence the user must still justify their final interpretations and acknowledge remaining uncertainty. As such, an experienced volcanologist can modify the scheme as needed while still maintaining its core principle of interpretive transparency.

Torres-Orozco et al. (2018) showed that grouping different lithofacies from multiple outcrops into broader lithofacies associations is a powerful approach to interpreting eruptive processes, and highlights the benefits of detailed fieldwork across multiple sites. The assessment scheme presented here cannot replace this kind of detail. Instead, it is hoped that the scheme’s simplicity encourages initial investigation and discussion of multiple deposits that may then form a starting point for further studies.

7 CONCLUSIONS

The assessment scheme developed here provides a new method for rapidly and consistently assessing volcanoclastic deposits to determine if they could have been emplaced by a pyroclastic flow. The scheme differs from previous identification systems as it explicitly acknowledges that different volcanoclastic processes can produce texturally similar deposits and hence result in interpretive uncertainty. Therefore, the final interpretation is presented in terms of which process(es) most confidently explain the observed features, while still recognizing other processes that

could have formed the deposit. This approach encourages assessment of all deposits regardless of size or preservation state. Recognition of pyroclastic flow deposits is important for quantifying the frequency and magnitudes of the hazard (Le Pennec et al., 2016), so rapid deposit assessments such as this can provide a valuable input for future probabilistic hazard assessments (e.g., Marzocchi et al., 2004) at high-risk volcanoes like Ruapehu.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/**Supplementary Material**.

AUTHOR CONTRIBUTIONS

JC developed the deposit assessment scheme and wrote the manuscript; BK, DG, and SC provided feedback for the assessment scheme and manuscript.

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SUPPLEMENTARY MATERIAL

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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APPENDIX: GLOSSARY OF ASSESSMENT CRITERIA

>50% Compositionally and Texturally Similar Volcanic Clasts

A broad assessment of whether the majority of volcanic clasts in the deposit are sufficiently similar that they might have come from the same source and hence may have been produced during the same volcanic eruption. The clasts may appear to have similar colors, surface textures, vesicularity, mineralogy, and similar weathering or alteration patterns.

Sorting

Poorly sorted deposits have components spanning a wide range of grain sizes. The presence of very large clasts is common but not a prerequisite for poor sorting; deposits containing significant amounts of both ash (<2 mm) and lapilli (2–64 mm) would still be considered poorly sorted.

Moderate/well sorted deposits contain clasts whose sizes are broadly similar. In fine-grained deposits (i.e., grain sizes <2 mm) larger clasts should be absent or very rare. In deposits containing mostly larger grain sizes (>2 mm), a small amount of finer material may be stuck to the surfaces of the larger clasts, but there should not be significant amounts of fines.

Layer is Part of a Stratified Deposit With Multiple Thin (mm to 10's cm) Layers

The deposit contains multiple layers whose textures are sufficiently similar that it is clear to the observer that they were all formed by the same volcanoclastic process. This assessment criteria is sufficiently broad that it applies to both individual events (e.g., a layered sequence of surge deposits originating from a single eruption) and longer term processes (e.g., a sequence of fall deposits from several different eruptions but all sharing textural similarities).

Clast Supported Lapilli, Mantles Undulating Topography With Even Thickness (if Observable)

This is particularly for deposits containing dominantly lapilli-sized clasts. The clasts should be in contact with each other, without significant interstitial matrix. The deposit should also maintain an even thickness over any underlying topography, though this may not be observable at all outcrops.

Channel or Valley Filling Geometry or Rapid Lateral Changes in Thickness

The deposit is laterally constrained by a channel or by surrounding topography (e.g., valley sides). This can be at any scale (centimetres to kilometers), so where the deposit extends beyond a single outcrop this should be considered when possible. Generally, any rapid change in deposit thickness suggests lateral emplacement mechanisms. Care should be taken to determine that thickness changes are original and not a result of later erosion.

Layer has Fine-Grained (Clay to Sand) Base Grading to Coarser Overlying Deposit, and/or Coarse-Tail Reverse Grading of Clasts, and/or Coarse-Tail Normal Grading of Lithic Fraction

Any fine-grained base should be part of the unit as a whole and typically grade into the overlying deposit. Coarse-tail grading refers to systematic vertical changes in grain size for only the coarser clasts. This typically occurs in deposits that have a finer matrix, where, for example the lapilli or bomb-sized clasts get larger (coarse-tail reverse grading) or smaller (coarse-tail normal grading) vertically up-sequence, but the finer matrix remains the same.

Bedforms (Cross-Beds, Ripples, Dunes, Pinch and Swell Bedding)

The assessment scheme makes no differentiation between bedforms produced by pyroclastic surges (typically shallower and longer wavelength) vs. fluvial/aeolian processes (typically steeper and shorter wavelength), but instead uses the presence of bedforms to differentiate these processes from other volcanoclastic processes that typically do not produce bedforms.

Sections Maintaining Pre-Transport Stratigraphy or Hummocky Topography ± Jigsaw-Fit Clasts

These features are typical of debris avalanche deposits. Hummocks should be clearly defined, indicating significant topography to the deposit's upper surface, and preferably with several hummocks observed. These may be metre-scale to many tens of meters in size. Since large sections of material move together en-mass in a debris avalanche, the deposit may contain hints of the source stratigraphy. The key here is identifying zones within an otherwise fragmental deposit that suggest sections moved together en-mass despite their fragmental nature. Examples include coherent patches of alteration/color or zones containing concentrations of distinct clasts. Similarly, jigsaw-fit clasts are larger clasts that have broken during transport and whose fragments have moved slightly apart, but have nonetheless remained sufficiently close to each other to still be identified as belonging to the same original clast.

Abundant Separate Crystal Fraction

Abundant free crystals in the ash-sized fraction of a deposit. The crystals should be the same compositions as the phenocryst phases in the dominant larger clasts.

Many Clasts Have a "Skin" or Chilled Margin Extending Around Most of the Clast Surface

A thin fine-grained or glassy rind that forms due to rapid cooling at the surface of a hot pyroclast. Breaking a clast open can show if the outer surface is texturally different to the very immediate (i.e., within < millimeter) interior, and can evidence a very thin "skin" typical of many pyroclasts even if a more pronounced chilled margin is not present.

If the "skin" or chilled margin is present around the entire clast, this shows the clast was formed when hot (i.e., juvenile/primary) and subsequently remained intact; and hence was not fragmented or abraded by the longer-term erosive system.

Elutriation Structures (can be Crystal and Lithic Rich and Fines Depleted)

Vertical pipe-like structures within the deposit evidencing vertical movement of gases or water that may have carried away finer or less dense material.

Evidence of Lateral Transport of Bomb-Sized Clasts (Abrasive Rounding, Discontinuous Lenses)

Any evidence that large clasts in the deposit have been laterally transported across the volcanic surface prior to deposition. Clasts may be noticeably rounded, imbricated, or show evidence of lateral interaction with surrounding clasts in the deposit (e.g., groups of larger clasts forming discontinuous lenses).

Several Accretionary Lapilli Preserved Within Layer

Accretionary lapilli are spherical aggregates of fine ash, typically with concentric layered interiors. They evidence co-eruptive interaction with water, and are often associated with pyroclastic surge and phreatomagmatic fall deposits. Due to their fragility, they are unlikely to survive significant transport in higher particle concentration flows or significant reworking.

Deposit is Located Far From Any Plausible Interpreted Vent or Outcrop Source for the Main Clast Types (e.g., Not Near Obvious Vent/Cone/Summit)

This criteria relies on user judgment, but is designed to identify material that is likely to have been transported a substantial distance before deposition. This criteria may be difficult to assess for older deposits.

High Temp Emplacement (e.g., Abundant In-Situ Thermally Jointed Clasts, Thermal Alteration of Whole Deposit, Abundant Charcoal, Clasts Have Aligned Magnetic Fabric, Deposit Welding)

This criteria looks for evidence that the deposit was hot at the time of emplacement. Thermally jointed clasts have prismatic interior cooling fractures radiating perpendicularly inwards from their surfaces that cause them to disintegrate when removed from the deposit. The clasts' fragility suggests that the fractures only developed after deposition, meaning they were still hot during transport. Deposit thermal alteration, extending across clasts and matrix, is often evidenced by pink or reddish alteration toward the top of the deposit. Magnetic field orientations of larger clasts can be determined using a magnetometer; consistent (aligned) field directions suggest the clasts only cooled through the Curie temperature after deposition. Deposit welding, where clasts have fused with surrounding clasts, is very clear evidence of high temperature deposition.

Charcoal fragments within a deposit suggest the interaction of high temperature material with vegetation and is a strong indicator of pyroclastic flows. However, unconsolidated pyroclastic flow deposits are easily reworked, so charcoal alone is a slightly less reliable indicator of hot emplacement. Therefore, any evidence that the deposit has not been reworked should be documented.