Inferring pyroclastic density current flow conditions using syn-depositional sedimentary structures

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Keywords:
Pyroclastic density current
Mount St Helens
Shear
Sedimentary structures
Kelvin-Helmholtz Instability
Flame Structures

Abstract

The processes occurring in the basal region of concentrated pyroclastic density currents (PDCs) influence the mobility, runout distance, and damage potential of a current, but directly observing these processes is extremely difficult. Instead we must investigate the deposits to glean information regarding the conditions of transport and deposition. The PDC deposits of the May 18, 1980 eruption of Mount St Helens (Washington, USA) contain sedimentary structures consisting of bed material reworked into undulose structures and recumbent flame structures. The structures vary over two orders of magnitude in size. Despite the large range in sizes, the structures remain self-similar in form, possibly suggesting a common mechanism for formation. The structures are interpreted as the record of granular shear instabilities, similar to Kelvin-Helmholtz instabilities, formed at the interface between a shearing, high concentration flow and the substrate in the moments just prior to deposition. The morphology of the structures suggests that the basal region of PDCs must be both highly concentrated and also highly mobile in the moments before final deposition, likely a result of elevated pore fluid pressures. We use a modified instability growth criterion to estimate PDC flow velocities at the time of formation; for the Mount St Helens PDCs, the velocity estimates range from 0.2 to 7.5 m s^{-1} with larger structures requiring higher flow velocities. Combining the velocity estimates with the dimensions of the structures suggests deposition rates of 4 to 32 cm s^{-1}. Such high deposition rates indicate that the deposits likely accumulated in a stepwise manner, rather than either progressively or *en masse*. Our findings motivate continued experimental and numerical work to understand how the formation of recumbent flame (and similar) structures affects subsequent flow behavior in terms of runout distance and hazard potential.

1.0 Introduction

The highly-concentrated basal region of pyroclastic density currents (PDCs) transports the vast majority of the total flow mass (Valentine 1987; Branney and Kokelaar 2002; Breard and Lube 2017); processes within this region influence the runout distance and damage potential of these dangerous volcanic phenomena (Sparks et al. 1993; Sulpizio et al. 2014; Dufek et al. 2015). Unfortunately, investigating the basal region of PDCs is notoriously challenging due to the difficulty of making direct observations in real time. Therefore, we investigate PDC deposits for insight into the enigmatic processes that occur at the flow base. PDC deposits record important information about transport and depositional processes occurring in the moments prior to, during, and following deposition (Branney and Kokelaar 2002). As such, we must continue to explore ways to derive quantitative information about the parent flows from PDC deposits to assess the accuracy of numerical models and ultimately to understand PDC behavior.

This study investigates deposits from topography-controlled, high-concentration PDCs, which generally have particle concentrations that range from a few volume percent to nearly max packing.

The generalized structure of PDCs is derived primarily from experimental observations, suggesting a non-depositional flow head followed immediately by the flow body below which a deposit aggrades (e.g. Girolami et al. 2010; Roche et al. 2010; Roche 2012; Lube et al. 2015; Breard and Lube 2017). Conditions in the flow head include high shear stress (Girolami et al. 2010) and an underpressure at the flow base (with respect to a static substrate) that produces an upward directed pressure gradient (Roche 2012; Roche et al. 2013), both of which may aid in entraining material from the bed. The flow body is thought to be a relatively low-shear environment with high pore fluid pressures that would hinder substrate entrainment. Despite these observations from experiments, many questions remain regarding the conditions and processes occurring in the basal region of PDCs. This basal region is the portion of the current through which any sedimentation must occur, and similarly controls erosive processes. Therefore, understanding processes in the basal region is integral to the interpretation of flow characteristics from PDC deposits.

One way to understand the processes of mass and momentum transfer at the base of PDCs is to investigate depositional evidence for the shear conditions at the flow-bed interface. Uniform, undisturbed, and undeformed ash fall layers overlain by thick ignimbrites are often cited as evidence that PDCs can be largely non-erosive and non-shearing (Valentine et al. 1989; Cas et al. 2011). Occasionally, however, flow-bed contacts suggest significant shear stress exerted on the bed. A number of studies identify depositional evidence for erosional channels (Sparks et al. 1997; Calder et al. 2000; Brand et al. 2014; Gase et al. 2017) or substrate derived lithics in subsequent PDC deposits (Buesch 1992; Bernard et al. 2014; Brand et al. 2016; Pollock et al. 2016), both of which may be related to shear stress exerted on the bed by the PDC. However, observations of deposits alone lend little insight into how these processes occur or how substrate erosion affects flow behavior.

The studies listed above describe outcrops that either demonstrate that erosion occurred while PDCs passed through an area, leaving behind scours and channels, or that PDCs deposited material eroded from some upstream source; fewer studies discuss outcrops with evidence for substrate erosion or deformation that occurred syn-depositionally. Syn-depositional substrate deformation captures in a single outcrop both the deformed substrate and deposits from the flow responsible for the deformation. Such an outcrop lends insight into the complex interplay between shear stress, erosion, and deposition occurring at the flow-bed interface.

Features associated with syn-depositional substrate deformation, including reverse faults (LaBerge et al. 2006), vortical structures at dune crests (Gianetti and Luongo 1994) and overturned and recumbent vortical features within well-bedded deposits (Douillet et al. 2015; Douillet et al. 2018), appear in the deposits from both dilute and concentrated PDCs. For example, Douillet et al. (2018) describe 'shark fin' structures that occur with periodicity in the deposits of dilute PDCs at Tungurahua Volcano, and attribute them to shear horizons related to traction carpets. For high-concentration PDCs, LaBerge et al. (2006) describe reverse faults formed syn-depositionally at the base of the Peperino Tipico Ignimbrite, at Monte Cimino, Italy. The reverse faults show that high-concentration PDCs can also transmit high shear stress to the substrate syn-depositionally. Finally, Rowley (2010) proposes a few examples of shear-related deformation structures in PDC deposits. The most notable structure is from the Tanjung formation in the Banten province of West Java, Indonesia, and they propose that the structures may be related to shear instabilities formed at the base of PDCs. The above field studies all demonstrate that behavior in the basal region of PDCs transitions back and forth from shearing to depositional over short timescales and that evidence for basal shear can be recorded in the PDC deposits, but using syn-depositional sedimentary structures to extract quantitative information about parent PDCs remains relatively unexplored.

Here we present evidence for syn-depositional basal shear recorded in deposits from the high-concentration PDCs produced during the May 18, 1980 eruption of Mount St Helens (MSH), USA. The PDC deposits contain numerous convex, undulose structures (Figure 1a) as well as recumbent flame structures (Figure 1c) located at contacts between flow units as well as within individual units. The undulose and recumbent flame structures range in size over almost two orders of magnitude, but are self-similar in form, potentially suggesting a similar mechanism of formation. The structures observed in the MSH deposits closely resemble sedimentary structures produced in previous analogue and numerical experiments (e.g. Goldfarb et al. 2002; Ciamarra et al. 2005; Rowley et al. 2011). We compare the recumbent flame structures in the deposits to similar structures produced in controlled laboratory environments to investigate the conditions under which the MSH flame structures formed. We use the dimensions of the recumbent flame structures to constrain flow concentration and depositional style as well as extract quantitative information about important flow parameters including basal slip velocity and deposition rates.

1.1 Terminology

In this work, we present two types of sedimentary structures observed in the PDC deposits from the May 18, 1980 eruption at MSH: undulose and recumbent flame structures. Both types of structures consist of a basal layer composed of reworked bed material and an overlying upper layer that shows no evidence of internal deformation. The deposits at MSH contain undulose structures that appear as a wavy, convex, basal layer consisting of alternating troughs and crests (Figure 1a). The recumbent flame structures have a concave lee surface with an overhanging arm, where the basal layer protrudes up into the overlying layer before bending, becoming sub-horizontal, and thinning in the downflow direction (Figure 1c).

The undulose structures share some morphologic similarities with traditional fluvial or aeolian bedforms such as regular spacing and their general convex shape. However, unlike ripples and dunes, the undulose structures generally lack internal stratification, a key characteristic of traditional bedforms. For this reason, we use the non-genetic, descriptive term undulose structures to describe the MSH structures.

Additionally, features similar to the recumbent flame structures described here are given many different names in the literature, including sheared, recumbent, or truncated flame structures (Sparks et al. 1985; Matsumoto et al. 2008; Rowley 2010; Rowley et al. 2011), vortical reworking features (Rowley et al. 2011), sheared wavelike structures (Roche et al. 2013), erosion waves (Farin et al. 2014), overturned laminae/ beds or vortex bedding (Douillet et al. 2015), and 'shark fin' structures (Douillet et al. 2018). Flame structure is a traditional soft sediment deformation term that describes a finger-like protrusion of a basal layer into an overlying layer. Unfortunately, in the literature, the term "flame structure" has become intertwined with formation mechanisms: either an unstable loading of a dense layer atop a less dense layer (i.e. Raleigh-Taylor instabilities) or earthquake-induced liquefaction, depending on the study (see Shanmugam 2017 for discussion of issues with terminology). Although the issue of implicit interpretation exists in the literature for the term "flame structures", the structures observed in the MSH deposits more closely resemble (recumbent) flame structures than any other previously described sedimentary structures. To avoid adding to the already cumbersome terminology and the genetic implications associated with some of the other terminology mentioned above, we follow Rowley et al. (2011) and use the non-genetic term recumbent flame structure to describe the structures observed in the MSH PDC deposits. However, we ultimately interpret a mechanism of formation for the recumbent flame structures that differs from either an unstable density contrast or earthquake-induced liquefaction.

2.0 Geologic Setting

2.1 Previous investigation of PDC deposits from the May 18, 1980 eruption of MSH

The May 18, 1980 eruption of MSH included a series of concentrated PDCs that produced stacks of sheet-like and elongated tongue and lobe-like deposits throughout the pumice plain (Figure 2a and 2b; Rowley et al. 1981; Kuntz et al. 1981). Following the eruption, vertical exposures of the PDC deposits existed only in walls of a few phreatic explosion craters. Consequently, for the few years following the eruption, observations of the deposits were mostly limited to surficial characteristics (Kuntz et al. 1981; Rowley et al. 1981).

Surficial observations allowed for investigation of at least the uppermost, late-stage flows. For example, levees and longitudinal ridges on the surface of the deposits constrained local flow directions for the latest PDCs (Rowley et al. 1981; Kuntz et al. 1990). Rowley et al. (1981) additionally describe the treacherous nature of walking on the deposits due to its quicksand-like nature. They note that a large rock thrown into the deposits caused "splashes and waves and tiny jets of air to escape from the surface". Rowley et al. (1981) also describe deflation of the PDC deposit surfaces of 1 meter or more in the hours to days following emplacement. Together, these observations support an interpretation of low permeability deposits with associated high gas retention rates. While these surficial observations are important, the lack of incision through the deposits in 1980 and 1981 prohibited rigorous investigation of PDCs deposited in the early or middle portions of the eruption.

In the nearly 40 years since the eruption, incision through the PDC deposits produced up to 40 vertical meters of new exposures along drainages cut throughout the pumice plain. A flood event in 1982 exposed more than 10 meters of new outcrop in the central pumice plain (Simon and Klimetz 2012). Criswell (1987) used the new exposures to produce the first detailed, chronostratigraphic correlation of the PDC deposits. Their study combines visual observations made during the eruption with a detailed investigation of the exposed deposits to correlate deposit characteristics to the eruption chronology. From their observations, Criswell (1987) distinguishes a lower, middle, and upper pyroclastic flow sequence and correlates each sequence to time periods during the May 18 eruption. However, Criswell (1987) also note that at the time of their study the lower sections of the deposits were not exposed.

Additional incision through the PDC deposits continued over the two decades following the study of Criswell (1987), resulting in an addition 20-30 m of new exposures (Simon and Klimetz 2012). Modern day outcrops include complete incision through what Criswell (1987) calls the lower sequence, as well as exposure of the basal contacts of the PDC deposits with both the debris avalanche and lateral blast deposits. Following this additional incision, Brand et al. (2014) revisited the PDC deposits and used the new exposures to refine PDC units and their correlation to the eruptive chronology. The following abbreviated chronostratigraphic description of the PDC deposits follows from observations of Christiansen and Peterson (1981), Rowley et al. (1981), Criswell (1987), and Brand et al. (2014).

2.2 Chronostratigraphy of PDC deposits at Mount St Helens

The May 18, 1980 eruption of Mount St Helens began with the largest volcanic flank failure in recent history when the over-steepened north flank of the volcano catastrophically failed and slid off to the north towards Johnston Ridge (Christiansen and Peterson 1981; Glicken 1996). Removal of the north flank led to rapid decompression of the cryptodome and hydrothermal system and initiated the lateral blast that travelled more than 20 kilometers to the north as a dilute density current (Christiansen and Peterson 1981). Following the landslide and the lateral blast, the eruption column stabilized into a Plinian ash column that rose 20 kilometers into the atmosphere (Christiansen and Peterson 1981).

The ash column steadily persisted until the early afternoon when the column destabilized and began to collapse, generating the series of PDCs that deposited throughout the pumice plain (Christiansen and Peterson 1981; Criswell 1987). Three main periods of PDC emplacement occurred during the afternoon of the eruption: an initial PDC phase when intensity of the eruption continued to build, a climactic phase, and a final phase associated with the waning of eruptive intensity (Criswell 1987; Brand et al. 2014). Brand et al. (2014) describe five primary PDC flow units deposited during these three phases. Units I and II are dominantly diffusely-stratified to massive lapilli tuffs emplaced during the first PDC phase. The PDCs that deposited Units I and II were confined by pre-existing topography and had highly concentrated basal regions that fluctuated between high and low shear environments (Brand et al. 2014). During the climactic phase of the eruption, the most voluminous PDCs deposited Units III and IV, both dominantly block-rich massive lapilli tuff with occasional lithic breccia and pumice lens facies. Brand et al. (2014) interpret that the Unit III and IV PDCs had highly concentrated basal regions and travelled up and around debris avalanche hummocks, eventually burying the pre-existing topography. The PDCs produced during the final phase are only found across the surface of the pumice plain and not exposed in outcrop; as such, Unit V is not discussed.

2.3 PDC Flow Directions

Previous studies constrain PDC flow directions in a variety of ways including both surficial features and outcrop observations. As mentioned above, Rowley et al. (1981) describe levees and ridges that define flow directions for the PDCs exposed at the surface. Kuntz et al. (1990) uses these surficial structures to map detailed flow directions for late-stage surficial PDCs. Brand et al. (2014) combine the surficial observations of Rowley et al. (1981) and Kuntz et al. (1990) with outcrop scale observations to refine estimates of flow directions. Synthesized observations of structural features such as levees, erosional scours, and pumice lens orientations provide information about flow direction at the outcrop scale (Brand et al. 2014). Observations of paleotopography also lends additional insight into flow directions for the PDCs.

3.0 Methods

Over the course of three field campaigns, we identified 11 undulose structures and 11 recumbent flame structures across 7 outcrops in the PDC deposits at MSH. We collected scaled digital images of each structure and measured its dimensions. When accessible, we excavated into the deposits a minimum of 30 cm to ensure the observed structures were not surficial features related to fluvial deposition or reworking.

We describe both the undulose and recumbent flame structures in terms of their length and height. For undulose structures, the length is measured as the distance between successive troughs, and the height is the distance from the lowest part of a trough to the top of the crest (Figure 1b). Recumbent flame structures have two main structural components, the trunk and the billow (Figure 1d). The trunk is the main body of the recumbent flame structure that protrudes up into the overlying layer from the otherwise horizontal substrate. The billow is the sub-horizontal arm of the wave that extends downstream and thins away from the trunk. For the recumbent flame structure, we define the length as the distance from the initial upward perturbation of the trunk to the end of the billow, and the height is the maximum upward displacement of the substrate from the otherwise horizontal contact. Although the morphology of the two types of structures is different, we consider the measurements for length and height comparable. We then use linear regression to investigate the correlation between the length and height of structures of different sizes.

4.0 Results

4.1 Syn-depositional sedimentary structures in the MSH PDC deposits

Both the recumbent flame and undulose structures are found throughout the MSH PDC flow Units II, III, and IV; the structures are located both at the contact between flow units and within single flow units. The recumbent flame structures at MSH range in size over two orders of magnitude, with lengths from 0.08 m to 17.9 m and heights from 0.04 to 1.80 m. Despite this significant range in size of the structures, they are self-similar in form; the length of the structures scales closely with the height (R^2=0.93; Figure 5). The undulose structures range in length from 4.0 to 35.7 m and heights from 0.25 to 4.1 m (Table 1). Most undulose structures are relatively symmetric and internally massive (Figures 1a, 4b, 4c), while others are asymmetric and have shorter upstream and longer downstream sides. One undulose structure shows faint internal bedding parallel to the lee face (AD-2a; Figure 4a). Similar to the recumbent flame structures, the length of the undulose structures scales with height (R^2=0.96;

Figure 5). No significant trends exist between height or length and distance from the vent for either type of structure.

The deformed bed is primarily earlier PDC deposits (Figures 3b-3d, 4b-4c), but also includes debris avalanche deposits (Figure 4a) and a single light-colored ash layer (Figure 3a). The debris avalanche deposits result from the catastrophic landslide that initiated the eruption and have a bimodal grain size distribution, with high proportions of fine ash and large blocks (Glicken 1996). In its only known exposure, the fine-grained, well-sorted ash layer sits just above the debris avalanche deposit (Figure 3a). Due to the well-sorted nature of the layer and its stratigraphic setting, we interpret the ash as co-ignimbrite fallout either from the lateral blast or one of the earlier PDCs. One set of undulose structures occurs in contact with debris avalanche deposits (Figure 4a), and a single set of recumbent flame structures occur in contact with the co-ignimbrite ash deposit (Figure 3a). The recumbent flame structure formed from the ash layer is the only structure with a basal layer that is significantly more fine-grained than the upper layer; in all other examples, the basal layer is either coarser or similar to the upper layer in its mean grain size.

The vast majority of undulose and recumbent flame structures occur with both the upper and basal layers consisting of PDC deposits. Given the general similarity of the PDC deposits, a distinct textural difference is necessary to observe the deformed contact. For example, a pumice-rich (e.g. Figure 3d) or dense lithic block-rich basal layers (e.g. Figure 1a, 1c, 4b) can define the contact and delineate the structure.

5.0 Discussion

5.1 Interpretations from field observations

The morphology of the structures allows for some general interpretations about flow characteristics including shearing conditions, flow direction, concentration, and deposition rates. The undulose and recumbent flame structures comprise a lower layer that is deformed and elongated, indicating that the PDCs interacted with and deformed the bed material during transport. The elongation of the structures suggests some amount of shear exerted on the flow-bed interface by the overriding flow. Therefore, we assume the elongation direction of the undulose and recumbent flame structures can be used a reliable indicator of approximate local flow direction. This idea is further supported by the coincidence of flow directions indicated by the undulose and recumbent flame structures with previous interpretations of flow direction (Brand et al. 2014).

Previous work on the MSH deposits interpret that the PDCs produced on May 18 were highly concentrated based on depositional characteristics (Brand et al. 2014, 2016; Pollock et al. 2016). Additionally, Breard et al. (2018) introduced a nondimensional dense-dilute number (T_{de-di}) that predicts the dominant transport mode (dense or dilute) based on geometry and granulometry of the resulting deposit. The dense-dilute number is defined as

$$T_{de-di} = \frac{A^3 d_{S,1/2}}{V^{5/3} L^2} \qquad (Eqn. 1)$$

where A is the inundation area, V is the total volume, L is the runout distance, and $d_{S,1/2}$ is the Sauter mean diameter at one half of the total runout. The Sauter mean diameter characterizes the importance of fluid drag on particle transport (Breard et al. 2018; Breard et al. 2019) and can be estimated by

$$d_S(mm) = 2^{-\left[\mu_{PSD}(\phi) + \frac{ln2}{2}\sigma_{PSD}{}^2(\phi)\right]} \qquad (Eqn\ 2.)$$

where μ_{PSD} and σ_{PSD} are the mean and standard deviation of the particle size distribution in ϕ units (full derivation in Breard et al. 2019). The transition in transport mode based on T_{de-di} occurs at ~3x10^{-3}, with greater values of T_{de-di} indicating dilute transport and values of T_{de-di} less than ~3x10^{-3} indicating dense transport.

We calculated T_{de-di} for the MSH PDC deposits using deposit geometry data from Rowley et al. (1981) and granulometry data from Brand et al. (2014). The T_{de-di} for the MSH deposits is 4.5x10^{-4}, which suggests the PDCs transported the bulk of their material as high-concentration, dense flows.

Two additional observations of the recumbent flame structures further support the interpretation of concentrated PDC conditions; first, the billow of the wave is generally at or above the highest point in the trunk of the wave, and second, the billow (composed of bed material) is underlain by flow deposit (Figure 3). If the flow were significantly expanded relative to the bed (i.e. low particle concentration) as the flow came to rest, the flow material underneath the billow would compact due to expelling of the gas (Figure 6). The compaction of the flow material would cause the billow to be depressed relative to the highest point of the wave trunk. But, because the billow is at or above the height of the trunk, compaction of the flow deposit during deposition must have been minor, indicating that the basal region of the flow was highly concentrated while the recumbent flame structure was growing and being deposited.

We interpret that the undulose structures also form due to shear exerted on the flow-bed interface; however, the lack of a billow prohibits constraining the flow concentration. One possibility is that the undulose structures form in lower concentration flows that cannot sustain the formation of a billow, and any material that is momentarily uplifted quickly falls back to the bed (Figure 6). A second possibility is that the undulose structures form in flows of similar concentration to the recumbent flame structures, but the undulose structures represent an earlier phase of growth. From both analogue and numerical experiments, a shearing, unstable interface is known to evolve from wavy, undulose forms to breaking waves (Goldfarb et al. 2002; Ciamarra et al. 2005), and the undulose structures possibly represent an earlier phase in the evolution of the recumbent flame structures.

Preservation of the recumbent flame structures in the deposits suggests the behavior in the basal region must quickly transition from non-depositional and shearing to rapid deposition. Growth of the recumbent flame structures requires uplift of the bed, and, if the bed is being uplifted, the flow must be non-depositional. But if the flow remains non-depositional following the onset of uplift, the structure will be completely amalgamated into the flow body, removing any evidence that the structure ever formed (Rowley et al. 2011). The preservation of the recumbent flame structure requires rapid deposition on the order of the height of the structure in the moments following the onset of bed uplift. Such rapid deposition implies that, given the thickness of the deposits, a current sustained for minutes to hours must only be depositing intermittently, with significant periods of non-deposition.

5.2 Mechanism of formation

5.2.1 Recumbent flame structures related to traditional bedforms?

Flemming (1988) compiled measurements of more than 1500 subaqueous and subaerial ripples and dunes and extracted relationships between bedform spacing and height for each group. Figure 5 shows the calculated least squares regression line for the relationship between spacing and height for subaqueous (blue line) and subaerial (green line) bedforms. As Flemming (1988) demonstrates, a different length to height relationship exists for subaqueous versus subaerial bedforms. A strong correlation exists between the height and the length of the MSH structures, but the relationship deviates from that of the subaqueous and subaerial bedforms (Figure 5). The heights of sedimentary structures in the MSH PDC deposits exceed the average height for either subaerial or subaqueous bedforms of the same length. In addition, more than half (55%) of the structures measured in the deposits at MSH plot above the maximum height of subaqueous bedforms of the same length (yellow line).

Similar to how different relationships exist for bedforms formed in water versus wind, the difference in transport processes and material for PDCs could explain the different relationship. However, the lack of internal stratification in all but one structure additionally distinguishes the MSH structures from traditional bedforms. While some similarities in morphology exist, the lack of internal stratification and the differences in length to height relationships suggest that a different mechanism produced the structures observed in the MSH PDC deposits.

5.2.2 Recumbent flame structures related to traditional soft sediment deformation?

Soft sediment deformation encompasses over 120 distinct features that record deformation of sediments prior to lithification (Shanmugam 2017). Two of the most common types of soft sediment deformation structures, load casts and flame structures, occur when a high-density layer sits unstably atop a lower density layer. The high density material sinks down into the underlying layer creating load casts, while finger-like injections of the less dense material protrude into the overlying layer creating flame structures (Allen 1984; Collinson and Thompson 1989; Collinson 1994; Owen 1996; Dasgupta 1998; Chiarella et al. 2016; Shanmugam 2017). Traditional flame structures are natural examples of Rayleigh-Taylor instabilities (Allen 1984). While classic flame structures rise vertically from the interface, they can also be sheared or recumbent in nature (Dasgupta 1998; Matsumoto et al. 2008). The recumbent flame structures somewhat resemble the recumbent flame structures in the MSH PDC deposits. However, key observations suggest that the MSH recumbent flame structures are not traditional flame structures.

At MSH, the recumbent flame structures most commonly occur at an interface between or within PDC deposits. Both the upper and lower layers commonly contain material of the same size and density characteristics. In the moments prior to final deposition of a PDC, the flow will be slightly expanded relative to the bed due to particle collisions during transport (Savage 1998) and diffusion of pore fluid pressure (Druitt et al. 2007; Breard et al. 2019). Therefore, the density of the PDC will always be equal to or less dense than the resulting deposit. These observations suggest that the vertical arrangement of a flowing PDC and an underlying deposit will be stable in terms of density stratification, prohibiting the formation of Raleigh-Taylor instabilities. Additionally, in some cases, the basal layer contains a high proportion of dense lithic blocks relative to the upper layer, indicating a higher bulk density relative to the upper layer (e.g. Figure 1c), further inhibiting the formation of traditional flame structures.

Although the recumbent morphology of the recumbent flame structures does suggest interaction between a fluid-like flow and a readily-deformable bed, the recumbent flame structures cannot be traditional flame structures. So-called recumbent flame structures in tsunami deposits have been interpreted to record syn-sedimentary deformation of the substrate due to shear stress exerted on the bed by the runup of the tsunami (Matsumoto et al. 2008). A similar, alternative mechanism must be responsible for the formation of the MSH recumbent flame structures.

5.2.3 Undulose and recumbent flame structures as granular shear instabilities

Previous experimental studies investigating the behavior of granular flows produce structures similar to those observed in the PDC deposits at MSH. For example, Goldfarb et al. (2002) investigate the behavior of two parallel granular flows traveling next to each other and shearing along a vertical contact. As slope increases, the contact between the two flows evolves from planar to wavy and eventually to the formation of breaking waves. The authors attribute the formation and growth of the waves to granular shear instabilities formed at the unstable interface between the two flows. However, the flows were shearing along a vertical contact and waves grew in the horizontal plane, without the restorative force of gravity. The aspect ratio and overall structure of the recumbent flame structures produced by Goldfarb et al. (2002) are similar to those observed in the PDC deposits at MSH (R^2 =

0.96), but the recumbent flame structures at MSH exist in a vertical plane along a horizontal contact where the effects of gravity cannot be ignored.

Ciamarra et al. (2005) use numerical simulations of horizontally flowing dry granular flows to study the interactions between the flow and its bed. The simulations demonstrate that the flows exert high shear stress on the bed, causing the contact to deform and become wavy due to the onset of shear instability growth. The waves are similar in shape and aspect ratio to the undulose structures observed at MSH. If the interface continues to evolve under high shear, the waves grow, develop billows, and begin to resemble breaking waves (Figure 7a; Ciamarra et al. 2005), similar in shape and aspect ratio to the recumbent flame structures at MSH. The authors suggest that the instabilities formed in the simulations are analogous to Kelvin-Helmholtz instabilities formed in shearing Newtonian fluids.

A series of recent laboratory experiments investigating granular flows with erodible, granular substrates produce similar structures to those in the numerical results of Ciamarra et al. (2005). Rowley et al. (2011) describe shear-derived vortical features formed as colored granular charges travel over a granular substrate (Figure 7b). Mangeney et al. (2010) and Farin et al. (2014) observe the down-flow migration of erosion waves whose amplitude and wavelength increase as slope increases (Figure 7c). Experiments of Roche et al. (2013) produce sheared flame structures propagating at the interface between a fine-grained granular substrate and both initially fluidized and dry granular flows. The flows in all of these experiments contain particles with the same density as those in the bed, and the particle concentration of the flows must be lower than that of the bed because the expansion due to particle collisions (Savage, 1998) and pore fluid pressure diffusion (Druitt et al. 2007). Therefore, the bulk density of the flows is less than that of the bed during growth of the waves. The authors of these studies all attribute the recumbent flame structures to granular shear instabilities that could be akin to Kelvin-Helmholtz instabilities (Rowley et al. 2011; Roche et al. 2013; Farin et al. 2014).

In addition, laboratory experiments demonstrate that underpressure relative to the ambient environment forms just behind the sliding head of granular flows (Roche et al. 2010). Pore fluid pressures in the substrate remain equal to the ambient, which leads to an upward-directed pressure gradient from the upper surface of the bed up into the flow (Roche et al. 2010). The upward pressure gradient is proposed to aid PDCs in the entrainment of large lithics from the bed (Roche et al. 2013; Roche 2015; Pollock et al. 2016; Roche et al. 2016). The numerical results of Ciamarra et al. (2005) demonstrate that such a pressure gradient would reinforce and even exacerbate the upward perturbation initially caused by the shear instability. As such, the combination of the pore fluid pressure gradient and surface instability likely both contribute to the growth of the structures observed in the experiments.

Based on the synthesized results from previous numerical and laboratory studies, we follow Rowley et al. (2011) and interpret the recumbent flame structures in the PDC deposits at MSH to be the record of granular shear instabilities formed during high shear conditions at the flow-bed interface. The majority of recumbent flame structures are located at unit contacts, suggesting that the instabilities formed during passage of the flow head. The flow head is thought to be a high shear environment (Girolami et al. 2010) and is associated with an upward directed pressure gradient (Roche et al. 2010), and thus it is perhaps not surprising that instabilities form under the flow head. However, the recumbent flame structures at MSH also exist within flow units, meters above the unit contact and deposited long after passage of the initial flow head. This observation indicates that high shear conditions also exist during intermittent periods of non-deposition from the body or perhaps during pulsating or unsteady flow behavior.

5.3 Implications for flow conditions

The formation of Kelvin-Helmholtz instabilities along an interface between two shearing Newtonian fluids can be predicted using an instability growth criterion (Kundu and Cohen 2004). The criterion shows that for given a density contrast between the two fluids, instabilities will develop when the velocity difference across the interface exceeds a minimum threshold. Rowley et al. (2011) and Farin et al. (2014) adapt the instability growth criterion for granular fluids and observe that the growth criterion predicts the formation of the shear instabilities produced in their experiments. We similarly use the instability growth criterion and measurements of the MSH recumbent flame structures to estimate the PDC velocity necessary to initiate instability growth. Because we cannot constrain the concentration of the flows during formation of the undulose structures (as discussed above), we use only the recumbent flame structures in these calculations. From Rowley et al. (2011), the instability growth criterion states that an interface will be unstable, leading to the growth of shear instability waves, when:

$$v_1 - v_2 \geq \sqrt{\frac{g\lambda}{2\pi}\left(\frac{\phi_2}{\phi_1} - \frac{\phi_1}{\phi_2}\right)} \qquad (Eqn. 3)$$

where v_1 and v_2 are the velocities of the flow and substrate, respectively, g is the acceleration due to gravity, and λ is the wavelength of the structure. $(\phi_2/\phi_1) - (\phi_1/\phi_2)$ is the relative solid volume fraction between the flow and the substrate, where ϕ_1 is the volume fraction of particles in the flow and ϕ_2 is the volume fraction particles in the substrate (Rowley et al. 2011). We assume the velocity of the substrate is negligible at the time of instability growth, and therefore:

$$v_1 \geq \sqrt{\frac{g\lambda}{2\pi}\left(\frac{\phi_2}{\phi_1} - \frac{\phi_1}{\phi_2}\right)} \qquad (Eqn. 4)$$

To solve for the velocity at the time of instability formation, we use the length of the recumbent flame structures and some assumptions about the solid volume fraction in the flow and substrate. As discussed above, preservation of the billows without distortion suggests a high solid volume fraction in the PDC during shear instability growth. Quantitatively constraining the solid volume fraction in PDCs from the deposits alone is impossible. However, many analogue experiments observe a basal region where solid volume fractions are only slightly expanded relative to the loose-packing solid volume fraction (Rowley et al. 2014; Breard and Lube 2017). Breard and Lube (2017) measure solid volume fractions in the dense basal regions of their experimental flows ranging from 20-60%. Gase et al. (2018) use ground penetrating radar to estimate the intergranular pore space in the PDC deposits at MSH. They find a solid volume fraction of 48-70%, which we use to constrain the solid volume fraction of the bed during deformation.

Using estimates of 20-60% and 48-70% for the solid volume fractions of the flow and substrate, respectively, along with the range of lengths for structures recorded in the deposits (0.08 - 17.9 m), the instability growth criterion (Eqn. 4) gives minimum basal slip velocities at the time of formation between 0.2-0.5 m s^{-1} for the smallest structures and 2.9-7.5 m s^{-1} for the largest structures (Table 1). These estimates assume a static bed; however, if the forces exerted on the substrate by the flow cause the velocity of the substrate to be non-zero, the flow velocities necessary to cause instability growth would increase. In addition, as the particle concentration of the flow approaches that of the substrate, the flow velocity necessary to cause instability growth decreases. Finally, elevated pore pressure within the fresh PDC deposits would decrease the particle concentration, further facilitating instability growth.

Experiments producing recumbent flame structures observe that the shear instabilities form behind the head of the current (Mangeney et al. 2010; Roche et al. 2013; Farin et al. 2014); as such, the calculated velocities for MSH likely do not reflect velocities at the flow front, but instead reflect a basal slip velocity at the time of instability formation. Furthermore, because several recumbent flame structures are found within flow units rather than the unit contacts, the velocity estimates may reflect the intermittent basal slip velocity of individual PDC pulses, or unsteadiness within a single current.

5.5 Implications for deposition

The recumbent flame structures suggest that in the moments prior to deposition the basal portion of the current exists in a highly concentrated state, and likely near max-packing. This highly concentrated layer must be at least as thick as the structure is tall (10s of cm to a few meters), but the layer remains mobile enough to begin mixing with the bed. The preservation of the structures in the deposits suggests that the basal portion of the flow transitions from mobile to depositionally frozen relatively quickly, and the morphology of the flame structures allows us to investigate the style of deposition both qualitatively and quantitatively.

Traditionally, deposition at the base of PDCs was argued to be either *en masse* or progressive in nature (Branney and Kokelaar 2002). *En masse* deposition occurs when the entire thickness of the flow comes to rest, preserving the vertical characteristics of the flow in the resulting deposit (Sparks 1976; Wright and Walker 1981; Carey 1991). In contrast, progressive aggradation suggests that material is incrementally accumulated from the base of a PDC during sustained deposition (e.g., Fisher 1966; Branney and Kokelaar 2002; Girolami et al. 2008; Girolami et al. 2010). A more recently proposed third depositional style combines *en masse* and progressive aggradation: stepwise aggradation. In stepwise aggradation, the deposit grows in pulses during punctuated periods of high deposition rates separated by periods of non-deposition or erosion (e.g. Sulpizio and Dellino 2008; Charbonnier and Gertisser 2011; Sarocchi et al. 2011; Macorps et al. 2018).

The MSH recumbent flame structures suggest intermittent periods of rapid deposition, consistent with the stepwise aggradation model. As mentioned above, the preservation of the recumbent flame structures requires rapid deposition of material on the order of the height of the structure in the moments following the onset of structure growth. The velocity estimates obtained in the previous section allow us to quantitatively constrain the rates of deposition. We assume that the bed material is uplifted and then carried horizontally a certain distance until it comes to rest. The timescale for deposition is given by the estimated flow velocity and the horizontal distance the material traveled prior to deposition, given by the length of the billow. By combining the height of the recumbent flame structure with this timescale for deposition, we can estimate a rate of deposition. For example, our velocity calculations suggest that growth of the largest structure (Figure 3a) was initiated when flow velocities were at least 2.9 m s^{-1}, and the material traveled 17.9 m prior to deposition. From this, we estimate a maximum deposition time of 6.2 seconds. Because the structure is 2.0 meters thick, the deposition rate is estimated to be at least 32 cm s^{-1}. A similar approach leads to deposition rates of 4 cm s^{-1} for the smallest recumbent flame structures. These are minimum estimates, based on the lowest calculated velocities. If we instead use the highest estimated velocities, the deposition rates are 83 cm s^{-1} and 25 cm s^{-1} for the largest and smallest recumbent flame structures, respectively.

If the entire deposit (8.2 m thick) containing the largest recumbent flame structure accumulated at the lowest estimated deposition rate, deposition would last ~26 seconds. Based on visual observations of the eruption, individual flows were likely emplaced over at least 10s of minutes (Criswell 1987). We therefore suggest that deposition of the MSH PDCs predominantly occurred in a stepwise fashion, with periods of high deposition rates followed by significant periods where currents were either bypassing (i.e. non-depositional) or erosional.

For comparison, the MSH deposition rates are an order of magnitude higher than those estimated for PDCs from other large eruptions. For example, Wilson and Hildreth (1997) suggest deposition rates of ≥0.25 cm s^{-1} for the Bishop Tuff, and Scott et al. (1996) suggest deposition rates of ≥1.23 cm s^{-1} for the PDCs generated during the June 15, 1991 eruption of Mount Pinatubo. The deposition rates for the Bishop Tuff and Mount Pinatubo are averaged over the entire thickness of the deposit assuming steady, progressive aggradation. Using structures similar to those observed in the MSH deposits may allow for further constraining deposition rates by identifying of sections of the deposits rapidly laid down.

6.0 Conclusions

The deposits of the high-concentration, column-collapse derived PDCs produced during the May 18, 1980 eruption of MSH record evidence for syn-depositional basal shear exerted by the PDCs on the substrate. High shear on the flow-bed interface results in the growth of granular shear instabilities that manifest themselves as recumbent flame structures preserved in the deposits. Similar granular shear instabilities occur in both numerical and experimental investigations and are regarded as being akin to Kelvin-Helmholtz instabilities. We use the dimensions of the recumbent flame structures and a modified instability growth criterion to calculate the minimum basal slip velocities at the time of instability initiation. Our velocity estimates range from 0.2-7.5 m s^{-1} for the MSH PDCs. The preservation of the recumbent flame structure suggests that the basal region of PDCs exists in a highly concentrated, but still mobile, state until the material in the basal flow region is rapidly deposited. Using the velocity estimates and the dimensions of the structures, we estimate minimum deposition rates between 4 and 32 cm s^{-1}. Given that most PDC outcrops at MSH are on the order of 10-20 meters thick, the entire thickness of an outcrop would have accumulated in a few minutes if these deposition rates were sustained. However visual observations show that individual flows were emplaced over tens of minutes. We therefore suggest the PDCs deposited in a stepwise fashion with periods of punctuated high rates of deposition in between extended periods of non-deposition or erosion.

In addition, we suggest that undulose and recumbent flame structures may often grow during deposition of a PDC and are either subsequently mixed into the current and destroyed, or not visible due to lack of contrasting textures. These structures, and the processes that form them, may be more common in the basal portion of concentrated PDCs that previously thought.

Finally, one of the greatest challenges in volcanology is constraining PDC flow, transport, and depositional conditions from a given deposit. Numerical simulations and scaled, granular flow experiments can help establish relationships between depositional features and conditions within the

PDC. While continued experimental work is necessary to fully validate the use of the instability growth criterion for fluidized PDCs, this approach shows promise for extracting quantitative information about flow conditions from PDC deposits.

Acknowledgments

This work was funded by a grant from the National Science Foundation (Award Number: 1347385). The authors thank Dr. Eric Breard, one anonymous reviewer, and the editor Dr. Richard Brown for their thoughtful and constructive comments that improved the quality of this manuscript.

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Figure 1a. Set of three undulose structures composed of course lithics found in the PDC deposits at Mount St Helens. Person shown for scale in red circle. 1b. Sketch showing measurement scheme for undulose structures where length is the distance between the toughs on either side of a crest, and height is the maximum vertical displacement from the contact. 1c. Example of recumbent flame structure found in the PDC deposits at Mount St Helens where a substrate composed of coarse lithics was sheared and partially mixed into the current as it flowed from left to right. Image modified from Brand et al. (2017). 1d. Sketch showing how measurements were made on recumbent flame structures.

Figure 2a. Aerial image of MSH showing extent of PDC deposition during the May 18, 1980 eruption. 2b. Inset from 2a showing locations of outcrops containing recumbent flame structures (red circle), undulose structures (blue circle), or both (red/blue circle). Yellow lines indicate inferred PDC flow paths from Brand et al. (2014). Both images taken from Google Earth.

Figure 3. Examples of recumbent flame structures found in outcrops B-3 (3a), B-2a (3b), and AD-3 (3c and 3d) with insets showing their structure. Images previously published in Brand et al. (2017). See Table 1 for outcrop details.

Figure 4. Examples of undulose structures found in the outcrops AD-2a (4a), AD-3.5 (4b), and AD-3 (4c) with insets showing their structure. See Table 1 for outcrop details.

Figure 5. Aspect ratio of the structures plotted as length versus height. Black circles indicate recumbent flame structures, gray diamonds indicate undulose structures, and solid black line is best-fit for all MSH structures. Also plotted are best-fit lines for subaqueous (blue long dashes) and subaerial (green short dashes) bedforms and the maximum height for subaqueous bedforms (yellow dots) from Flemming (1988).

Figure 6. Schematic of the onset, growth, and deposition of granular shear instability at the flow-bed interface for different concentration currents. PDCs with high-concentration basal regions are able to preserve recumbent flame structures, while low concentration PDCs are not able to support the arm of the recumbent flame structure and it collapses back to the bed.

Figure 7. Examples from previous studies producing recumbent flame structures. 6a. Sketch after Ciamarra et al. (2005) showing evolution of sheared interface during numerical simulations. 6b. Shear induced mixing features adapted from Rowley et al. (2011). 6c. “Erosion waves” produced in experiments of Farin et al. (2014).

Table 1. Measurements of undulose and recumbent flame structures and details regarding the outcrops in which they are found.