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Sequential fragmentation/transport theory, pyroclast size–density relationships, and the emplacement dynamics of pyroclastic density currents — A case study on the Mt. St. Helens (USA) 1980 eruption

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ABSTRACT

Pyroclastic density currents (PDCs) are the most dangerous hazard associated with explosive volcanic eruptions. Despite recent advancements in the general understanding of PDC dynamics, limited direct observation and/or outcrop scarcity often hinder the interpretation of specific transport and depositional processes at many volcanoes. This study explores the potential of sequential fragmentation/transport theory (SFT; cf. Wohletz et al., 1989), a modeling method capable of predicting particle mass distributions based on the physical principles of fragmentation and transport, to retrieve the transport and depositional dynamics of well-characterized PDCs from the size and density distributions of individual components within the deposits. The extensive vertical and lateral exposures through the May 18th, 1980 PDC deposits at Mt. St. Helens (MSH) provide constraints on PDC regimes and flow boundary conditions at specific locations across the depositional area. Application to MSH deposits suggests that SFT parameter distributions can be effectively used to characterize flow boundary conditions and emplacement processes for a variety of PDC lithofacies and deposit locations. Results demonstrate that (1) the SFT approach reflects particle fragmentation and transport mechanisms regardless of variations in initial component distributions, consistent with results from previous studies; (2) SFT analysis reveals changes in particle characteristics that are not directly observable in grain size and fabric data; and (3) SFT parameters are more sensitive to regional transport conditions than local (outcrop-scale) depositional processes. The particle processing trends produced using SFT analysis are consistent with the degree of particle processing inferred from lithofacies architectures: for all lithofacies examined in this study, suspension sedimentation products exhibit much better processing than concentrated current deposits. Integrated field observations and SFT results provide evidence for increasing density segregation within the depositional region of the currents away from source, as well as for comparable density-segregation processes acting on lithic concentrations and pumice lenses within the current. These findings further define and reinforce the capability of SFT analysis to complement more conventional PDC study methods, significantly expanding the information gained regarding flow dynamics. Finally, this case study demonstrates that the SFT methodology has the potential to constrain regional flow conditions at volcanoes where outcrop exposures are limited.

1. Introduction

Pyroclastic density currents (PDCs) are ground-hugging currents of gas, ash, and pyroclasts that travel at high velocities down the flanks of volcanoes (Francis, 1993; Sparks et al., 1997). PDCs are the most dangerous hazard associated with explosive volcanic eruptions, but because of current opacity and the risk inherent to observing PDCs in real time, the controls on transport and depositional processes are poorly understood. Volcanologists analyze PDC deposits to reconstruct flow characteristics. The flow information inferred from the study of PDC deposits is used to establish primary controls on runout distance, dynamic pressure, and other hazardous aspects of these currents (e.g., Valentine, 1998; Calder et al., 2000; Allen, 2001; Bourdier and Abdurachman, 2001; Dellino et al., 2011). However, outcrop exposure is often incomplete, and the extent to which local depositional characteristics are representative of the parent current transport and depositional processes

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at given spatial and temporal locations is still uncertain (e.g., Druitt, 1995; Giordano, 1998; Wohletz, 1998; Taddeucci and Wohletz, 2001; Branney and Kokelaar, 2002; Taddeucci and Palladino, 2002).

For this study, our objectives are to find and test methods that link PDC deposit characteristics with parent flow dynamics. We examine the solid fraction of PDCs, which is made up of discrete components including juvenile pumice and vitric glass fragments, accidental lithics, and free crystals. During both regional transport (i.e., transport from the PDC source to the depositional site) and local deposition, the components are preferentially sorted as a function of their size, density, and shape characteristics, resulting in particle distributions that can be identified at the outcrop scale (Wohletz et al., 1989; Calder et al., 2000; Taddeucci and Wohletz, 2001; Burgisser and Bergantz, 2002; Taddeucci and Palladino, 2002). We analyze the particle distributions in PDC deposits using sequential fragmentation/transport theory (SFT), a methodology that predicts mass distributions based on the physical principles of fragmentation and transport (Wohletz et al., 1989).

2. Field location: Mt. St. Helens

The MSH eruption began on the morning of May 18th with the collapse of the bulging edifice and subsequent debris avalanche. The debris avalanche was followed by a lateral blast that resulted from the decompression and rapid expansion of magma beneath the collapsed edifice (Kieffer, 1981; Fisher, 1990). The Plinian eruption that commenced after the blast continued throughout the day, reaching the climactic phase in the late afternoon (Christiansen and Peterson, 1981; Rowley et al., 1981; Criswell, 1987). The increase in eruptive intensity through the early afternoon and during the climactic phase produced multiple PDCs generated by column collapse events, which buried the area north of the crater under 10s of meters of PDC deposits (the present-day pumice plain; area with red arrows in Fig. 1).

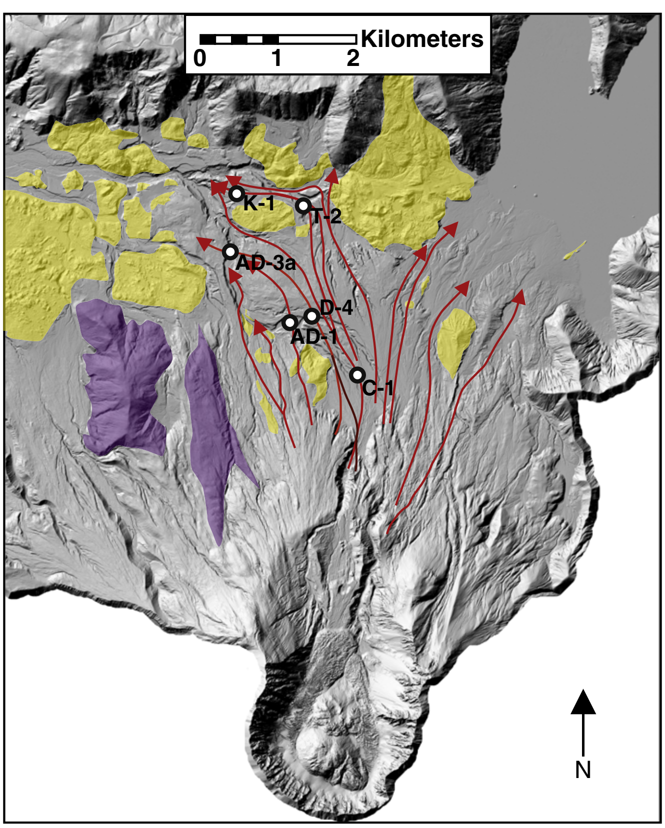

Fig. 1. LiDAR image of the Mt. St. Helens crater and pumice plain. The regions highlighted purple indicate pre-1980 eruption topography, and the regions highlighted yellow indicate exposed debris avalanche hummock deposits. Red arrows indicate dominant flow direction for Units III and IV as interpreted based on field observations and deposit characteristics. Outcrop names and locations are indicated; drainages and outcrops correlate with those described in Brand et al. (in press).

Deep drainage erosion over the past 30 yr has provided kilometers of excellent exposure through the MSH deposits, allowing a detailed study of deposit structures to be conducted (cf. Pollock and Brand, 2012; Pollock, 2013; Brand et al., in press). Readers are referred to Brand et al. (in press) for a detailed analysis and interpretation of each MSH flow unit and outcrop location. Here we restrict our descriptions to the general depositional features and trends that are relevant to our research. 'Proximal' refers to outcrops <5.25 km from the crater, 'medial' refers to outcrops 5.25–7.25 km from the crater, and 'distal' refers to outcrops >7.25 km from the crater. Lithofacies abbreviations are modified from Branney and Kokelaar (2002) and are presented in Table 1.

2.1. Mt. St. Helens PDC flow units

Four major PDC flow units are identified in the drainages that transect the pumice plain, which extends from the break in slope north of the MSH crater to Johnson Ridge (Figs. 1 and 2). We associate Units I and II with the waxing afternoon phase of the eruption (termed the early ash flow phase by Criswell, 1987), and Units III and IV with the climactic phase of the eruption (termed the climactic ash flow phase by Criswell, 1987).

Units I and II represent the first PDCs to traverse the MSH pumice plain. The base of Unit I is rarely exposed, but where observed it is in contact with debris avalanche and blast deposits from the beginning phases of the eruption. Overall, both Units I and II are thicker (>10 m) and dominated by massive lapilli tuff (*mLT*) in the distal regions, and thinner (<6 m) and dominated by stratified (*sLT*) to diffusely-stratified and diffusely cross-stratified (*dsLT*) deposits in the medial distances (Table 1). Both flow units grade between *mLT*, *dsLT*, and *sLT* over short vertical and lateral distances (vertical gradations occur within meters; lateral gradations over 10s–100s of meters), and the deposits generally become finer grained and have tighter sorting with distance from source (see Fig. 4 in Brand et al., in press). Pumice lenses are common in both flow units and increase in abundance in the distal regions. The contacts between Units I and II, and between Units II and III, are characterized by thin (<50 cm), somewhat laterally continuous massive tuffs.

The massive nature and general lack of fabric within the distal deposits suggests that they were produced by a concentrated current with negligible shear stress. However, the proximal stratified and diffusely-stratified deposits indicate depositional regions where traction and/or granular flow boundaries occurred, likely as a consequence of variability in surface roughness, and reflect the inherent unsteadiness within the currents that produced Units I and II. The laterally continuous and massive nature of the fine ash layer between the units suggests that deposition occurred via direct fallout (cf. Branney and Kokelaar, 2002). Thus we interpret that the fine ash layers settled from a co-ignimbrite ash cloud, the waning tail of the current, or some combination of the two.

Table 1
Lithofacies symbols (modified from Branney and Kokelaar, 2002).

Symbol	Lithofacies
mLT	Massive lapilli tuff
mlBr	Massive lithic breccia
sLT	Stratified lapilli tuff
xsLT	Cross-stratified lapilli tuff
dsLT	Diffuse stratified lapilli tuff
lensP	Pumice lens