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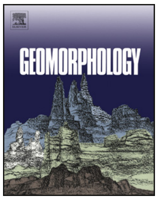

Rainfall-runoff properties of tephra: Simulated effects of grain-size and antecedent rainfall

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ABSTRACT

Rain-triggered lahars (RTLs) are a significant and often persistent secondary volcanic hazard at many volcanoes around the world. Rainfall on unconsolidated volcaniclastic material is the primary initiation mechanism of RTLs: the resultant flows have the potential for large runout distances (>100 km) and present a substantial hazard to downstream infrastructure and communities. RTLs are frequently anticipated in the aftermath of eruptions, but the pattern, timing and scale of lahars varies on an eruption-by-eruption and even catchment-by-catchment basis. This variability is driven by a set of local factors including the grain size distribution, thickness, stratigraphy and spatial distribution of source material in addition to topography, vegetation coverage and rainfall conditions. These factors are often qualitatively discussed in RTL studies based on post-eruption lahar observations or instrumental detections. Conversely, this study aims to move towards a quantitative assessment of RTL hazard in order to facilitate RTL predictions and forecasts based on constrained rainfall, grain size distribution and isopach data. Calibrated simulated rainfall and laboratory-constructed tephra beds are used within a repeatable experimental set-up to isolate the effects of individual parameters and to examine runoff and infiltration processes from analogous RTL source conditions.

Laboratory experiments show that increased antecedent rainfall and finer-grained surface tephra individually increase runoff rates and decrease runoff lag times, while a combination of these factors produces a compound effect. These impacts are driven by increased residual moisture content and decreased permeability due to surface sealing, and have previously been inferred from downstream observations of lahars but not identified at source. Water and sediment transport mechanisms differ based on surface grain size distribution: a fine-grained surface layer displayed airborne remobilisation, accretionary pellet formation, rapid surface sealing and infiltration-excess overland flow generation whilst a coarse surface layer demonstrated exclusively rainsplash-driven particle detachment throughout the rainfall simulations. This experimental protocol has the potential to quantitatively examine the effects of a variety of individual parameters in RTL initiation under controlled conditions.

1. Introduction

Rainfall on unconsolidated volcaniclastic material, typically pyroclastic density current (PDC) and/or ash-fall deposits, is the primary initiation mechanism of secondary, rain-triggered lahars (RTLs). These flows pose a significant hazard to downstream infrastructure, with impacts ranging from damage to building contents via flow inundation, to complete destruction and burial of structures (Jenkins et al., 2015). RTLs often pose a long-lived secondary hazard, with discrete large eruptions resulting in significant catchment disturbance for many decades (Major et al., 2000; Gran and Montgomery, 2005; Major and Yamakoshi, 2005; Van Westen and Daag, 2005; Major and Mark, 2006). The combination of intense rainfall and a source of volcaniclastic material required for RTL initiation is particularly common throughout the tropics and subtropics, and has been documented at volcanoes including Mayon (Arguden and Rodolfo, 1990; Rodolfo and Arguden, 1991; Orense and Ikeda, 2007; Paguican et al., 2009), Pinatubo (Arboleda and Martinez, 1996; Martinez et al., 1996; Rodolfo et al., 1996; Tungol and Regalado, 1996; Van Westen and Daag, 2005), Merapi (Lavigne et al., 2000a,b; Lavigne and Thouret, 2003; de Bélizal et al., 2013), Semeru (Lavigne and Suwa, 2004; Doyle et al., 2010; Dumaisnil et al., 2010; Thouret et al., 2014), Soufriere Hills (Barclay et al., 2007), Colima (Davila et al., 2007; Capra et al., 2010) and Tungurahua (Jones et al., 2015), illustrating the global extent of locations with significant documented histories of RTL activity.

The initiation of RTLs typically occurs via either particle detachment by rainsplash erosion and subsequent transport by overland flow (Segerstrom, 1950; Waldron, 1967), rill erosion caused by surface runoff (Nammah et al., 1986; Leavesley et al., 1989; Yamakoshi and Suwa, 2000; Lavigne and Thouret, 2003; Major and Yamakoshi, 2005; Barclay et al., 2007) or by shallow landsliding of saturated tephra layers

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above basal décollement surfaces (Rodolfo and Arguden, 1991; Hodgson and Manville, 1999; Manville et al., 2000; Jensen et al., 2013) (Fig. 1). Numerous temporally and spatially variable factors contribute towards these lahar initiation processes including grain size distribution (Pierson et al., 2013), thickness (Janda et al., 1996; Scott et al., 1996; Manville et al., 2000), extent of compaction (Manville et al., 2000) and volatile content (Waldron, 1967) of pyroclastic material; vegetation cover (Yamakoshi and Suwa, 2000; Barclay et al., 2007; Ogawa et al., 2007; Alexander et al., 2010) and type (Capra et al., 2010); rainfall intensity and duration (Rodolfo and Arguden, 1991; Lavigne et al., 2000b; Van Westen and Daag, 2005; Hikida et al., 2007; Okano et al., 2012); slope angle (Pierson et al., 2013) and antecedent rainfall (Lavigne et al., 2000b; Barclay et al., 2007; Okano et al., 2012; Jones et al., 2015) (Fig. 2).

The deposition mechanism of the volcaniclastic material, usually either PDC or ash-fall deposits, plays an important role in controlling spatio-temporal variability of RTL initiation. PDC deposits typically contain more fines as a result of a lack of aerodynamic sorting, are generally valley confined, and usually eroded by headward migration of knickpoints and channel widening/bank collapse (Manville et al., 2009; Pierson and Major, 2014). Ash-fall deposits mantle the topography, are thinner, more widely distributed, better sorted, and easily eroded by rilling, uniform sheetwash or shallow landsliding (Pierson and Major, 2014). They typically display an exponential decrease in particle size and deposit thickness with increased distance from the vent but dispersal patterns can be more complex (e.g. Brazier et al., 1983). The surface of ash-fall deposits often undergoes post-deposition surface sealing and crusting as a result of raindrop impact and/or chemical precipitation, a process which increases surface resistance to erosion but also increases runoff (Waldron, 1967). Once the surface crust has been disturbed, runoff can remobilise underlying material, potentially resulting in RTL initiation (Waldron, 1967). PDC deposits are described by Pierson and Major (2014) as loose and highly erodible by rainfall and streamflow; although large, hot PDCs can produce deposits featuring welded zones which are more resistant to erosion. Ash-fall can damage vegetation via abrasion, weight-induced failure, burial, chemical damage or interference with leaf surface metabolic activity (Alexander et al., 2010; Swanson et al., 2013; Pierson and Major, 2014). PDCs can sand blast, burn, fell and in some examples strip and remove all vegetation within a valley (Pierson, 1985; Pierson and Major, 2014; Stinton et al., 2014).

Rainfall intensity/duration relationships have been a frequently utilised method of post-eruption RTL analysis. Studies at volcanoes including Pinatubo (Arboleda and Martinez, 1996; Tungol and Regalado, 1996; Van Westen and Daag, 2005), Mayon (Rodolfo and Arguden, 1991), Tungurahua (Jones et al., 2015), Merapi (Lavigne et al., 2000b) and Colima (Capra et al., 2010) have used this method, which typically displays a power-law relationship that suggests that lahar initiation occurs along a continuum from short duration, high intensity rainfall events to long duration, low-intensity events. Intensity/duration analysis compiles datasets of identified and/or instrumentally-detected lahars and identifies the range of rainfall conditions under which lahars can potentially occur. Probabilistic analysis and forecasting of lahars has been undertaken at Tungurahua (Jones et al., 2015) using peak rainfall intensity and antecedent rainfall data. Probabilistic analysis of this nature uses the lahar and rainfall databases to examine the likelihood of lahars under different rainfall conditions and then applies it to real-time rainfall data to make lahar forecasts. Probabilistic lahar forecasting acknowledges the uncertainty present in the lahar triggering rainfall range identified during intensity/duration analysis. Such uncertainty is difficult to constrain during field-based studies due to the challenges of observing lahar initiation zones, given their typical proximity to the active vents of frequently eruptive volcanoes. This access issue, in combination with the complex nature of RTL initiation processes, makes it difficult to isolate the impacts of individual parameters upon RTL initiation. Rainfall simulation experiments are one method of approaching this issue, and have previously been utilised to study rainfall-runoff relationships in other disturbed earth systems such as wildfire-affected areas. Such simulations have typically been either field-based (e.g. Pierson et al., 2008; Woods and Balfour, 2010; Huang et al., 2013; Zhao et al., 2014) or lab-based (e.g. Bradford et al., 1987; Singh et al., 2000; Jomaa et al., 2013; Wang et al., 2014) and have focused on a variety of parameters using different slope angles, rainfall regimes and bed compositions (Römkens et al., 2002; Liu et al., 2011; Huang et al., 2013).

Previous rainfall simulation studies have indicated that enhanced vegetation cover, and thus the process of vegetation recovery, increases infiltration and decreases runoff and erosion rates. This is a result of heightened permeability due to surface seal and crust disruption as well as increased soil stability and rainfall interception (Morgan et al., 1997; Major and Yamakoshi, 2005; Cerda and Doerr, 2008; Huang et al., 2013; Zhao et al., 2014). Elevated slope angle and rainfall intensity increase runoff rates due to heightened occurrence of infiltration-excess overland flow (Horton, 1933; Luk, 1985; Liu et al., 2011; Huang et al., 2013; Jomaa et al., 2013). High surface moisture content and thus surface water potential, often induced by significant antecedent rainfall or long-duration rainfall events, acts to increase rainsplash-driven particle detachment in inter-rill regions via a reduction in surface shear strength (Luk, 1985; Bryan, 2000). In addition, increased surface roughness was shown by Römkens et al. (2002) to increase sediment yield under pre-defined rainfall conditions and rill development is heightened on steeper slopes (Gómez et al., 2003). Zhao et al. (2014) described runoff mechanisms on grassland plots under rainfall simulation conditions as infiltration-excess overland flow-dominant

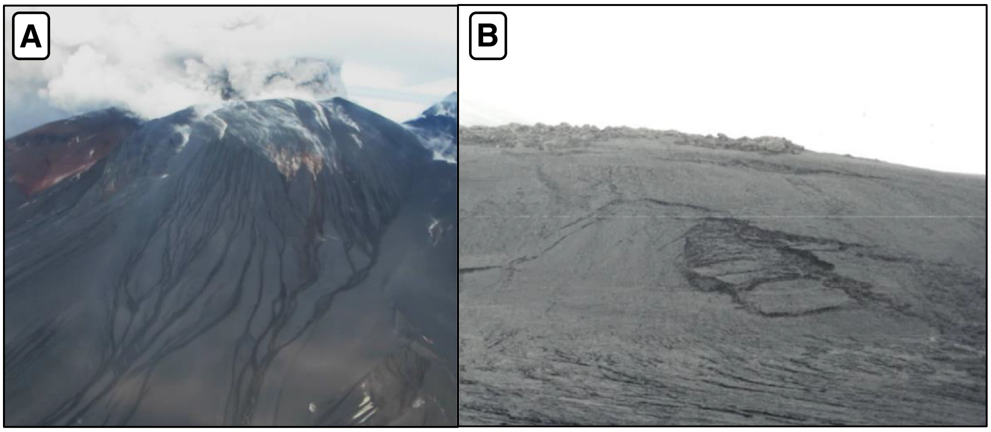

Fig. 1. Photographs illustrating erosion mechanisms of pyroclastic deposits. A) Rill network and channel development on the upper edifice of Calbuco Volcano, Chile (April 2015). B) Shallow landsliding of the tephra blanket in the Mangatoetoenui catchment of Ruapehu, New Zealand (October 1995). The 0.20 m-thick tephra layer was sliding on a thin (sub-cm) layer of fine-grained phreatomagmatic ash that was frozen to the underlying snow and ice.